Liquid Crystal Optics in the Far Infrared (THz)

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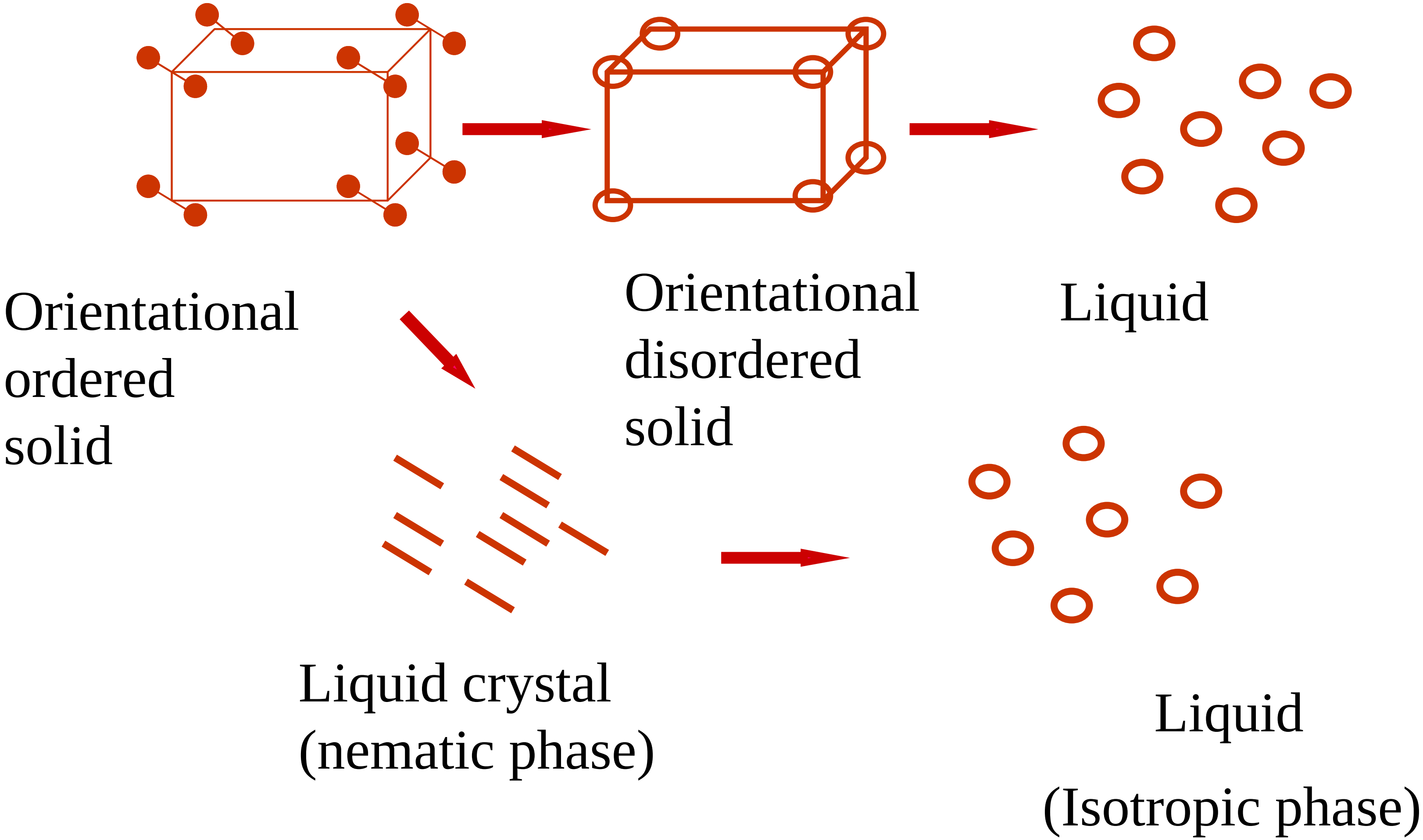
Outline

- Motivation and Objectives
- Liquid Crystals (LC) and THz Techniques: Basics
- THz Optical Constants of LC
- Examples of LC THz devices: phase shifter, quarter-wave compensator, filters

Motivation and Objectives

- Motivations:
  - Increasing demands for THz quasi-optic components.
  - LC has played an important role in the visible optics as well as electro-optics and could be as eminent in THz optics.
- Objectives:
  - Characterization of LCs in the THz regime
  - To develop THz photonic devices with LC-enabled functionality

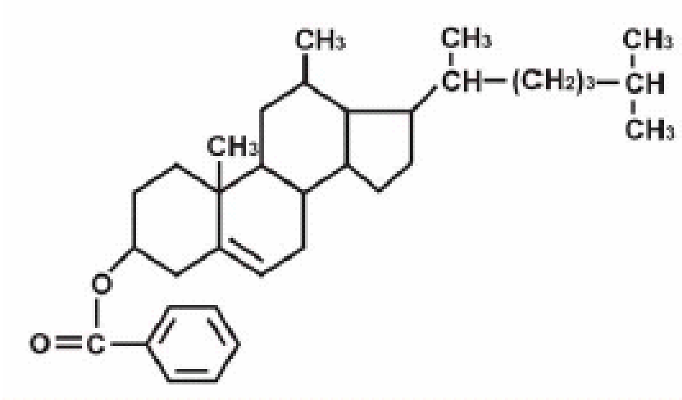
Liquid Crystal: A Unique State of Matter



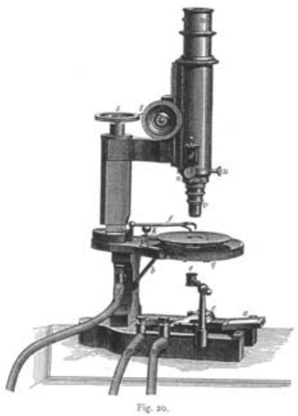
The first Liquid Crystal

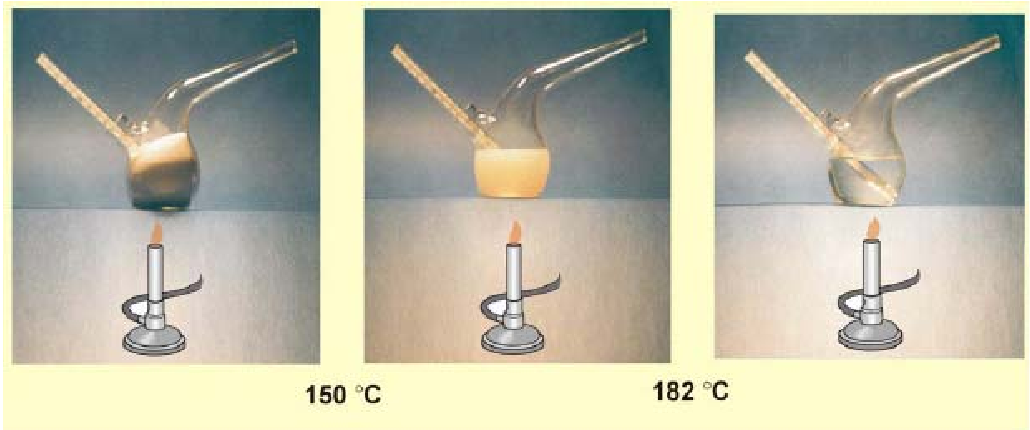
Friedrich Reinitzer, 1857-1927

(image from www-ub.kfunigraz.ac.at)



cholesteryl benzoate: related to cholesterol





Otto Lehmann's polarizing microscope

(From his book, 1900)

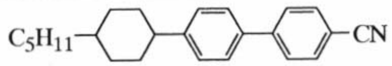
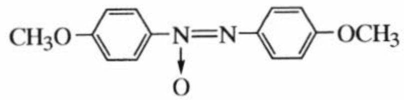
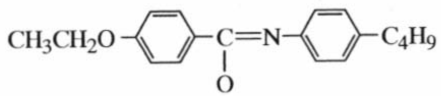
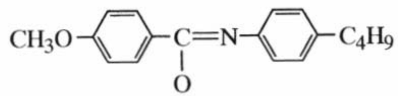
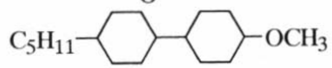
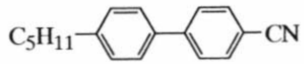
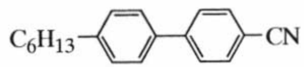
F. Reinitzer, Z. Phys. Chem. **9**, 241 (1988)

O. Lehmann, ibid., **4**, 262 (1989)

Properties of LC Materials

- LC is state of matter intermediate between solid and amorphous liquid
  – Liquid with
    ordered arrangement of molecules
  – Molecules with
    orientation order (like crystals) but
    lack **positional order** (like liquids)
- Organic substances with
    anisotropic molecules that are
    highly enlongated or flat
- Ordering leads to **anisotropy** of
  – **Mechanical properties**
  – **Electrical properties**
  – **Magnetic properties**
  – **Optical properties**

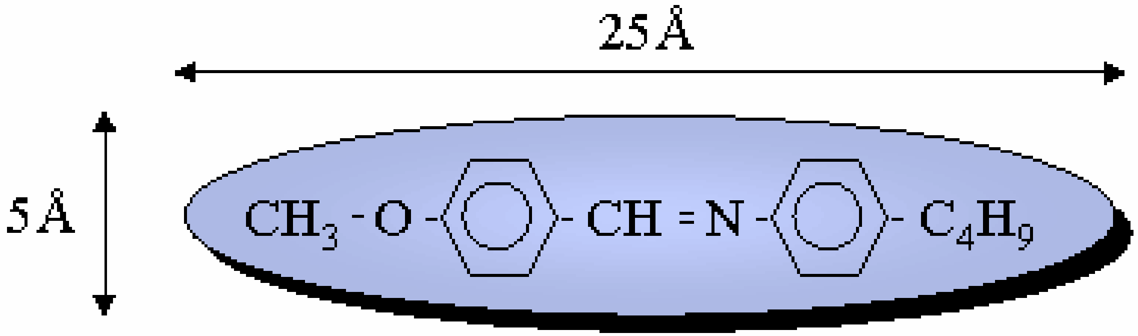
Table 1.1. Liquid Crystal Materials

Name	Formula	Nematic Range (°C)
BCH-5		96–219
PAA		118–135.5
EBBA		35–77
MBBA		22–47
CCH-501		29–36.8
5CB		24–35
6CB		15–29

Yeh & Gu

Building Blocks of Liquid Crystals

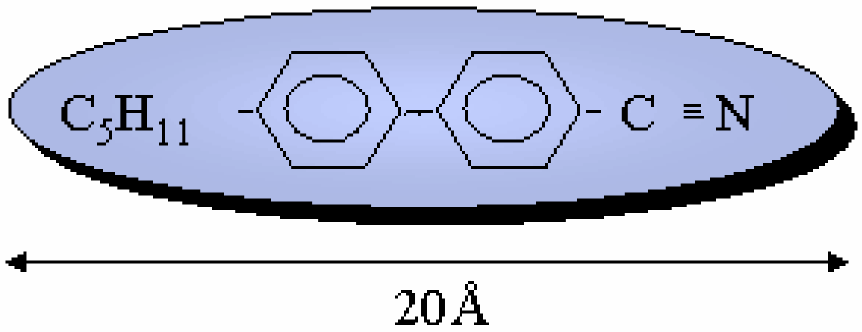
rod like (calamitic):



MBBA

(4-methoxybenzyliden-4´-butylanilin)

C 22° N 47° I



5CB

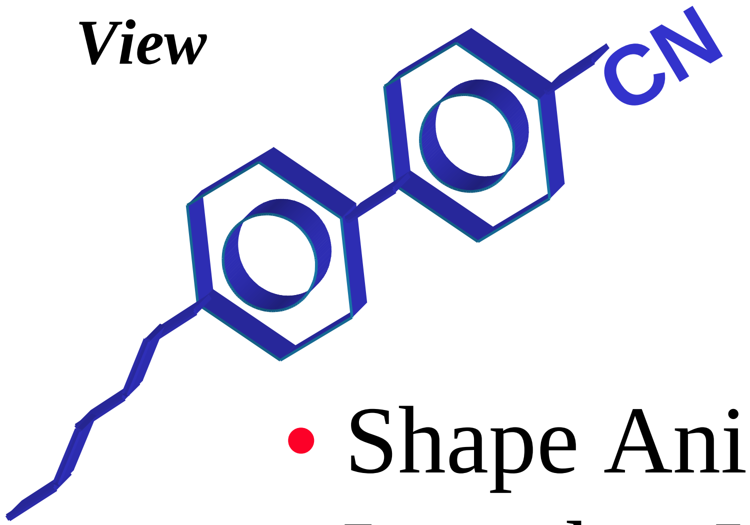
(4-pentyl-4´-cyanobiphenyl)

C 18° N 36° I

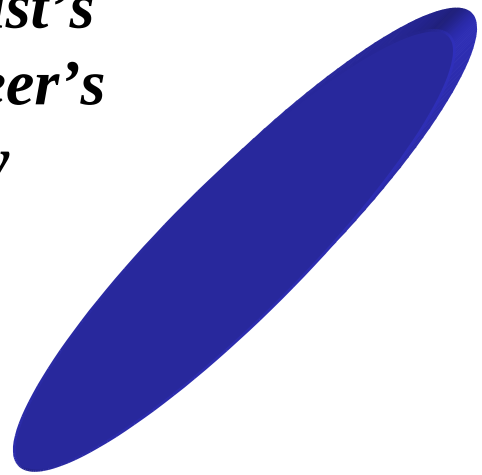
others: **disk like (discotic)**

Different Points of View

Chemist's View



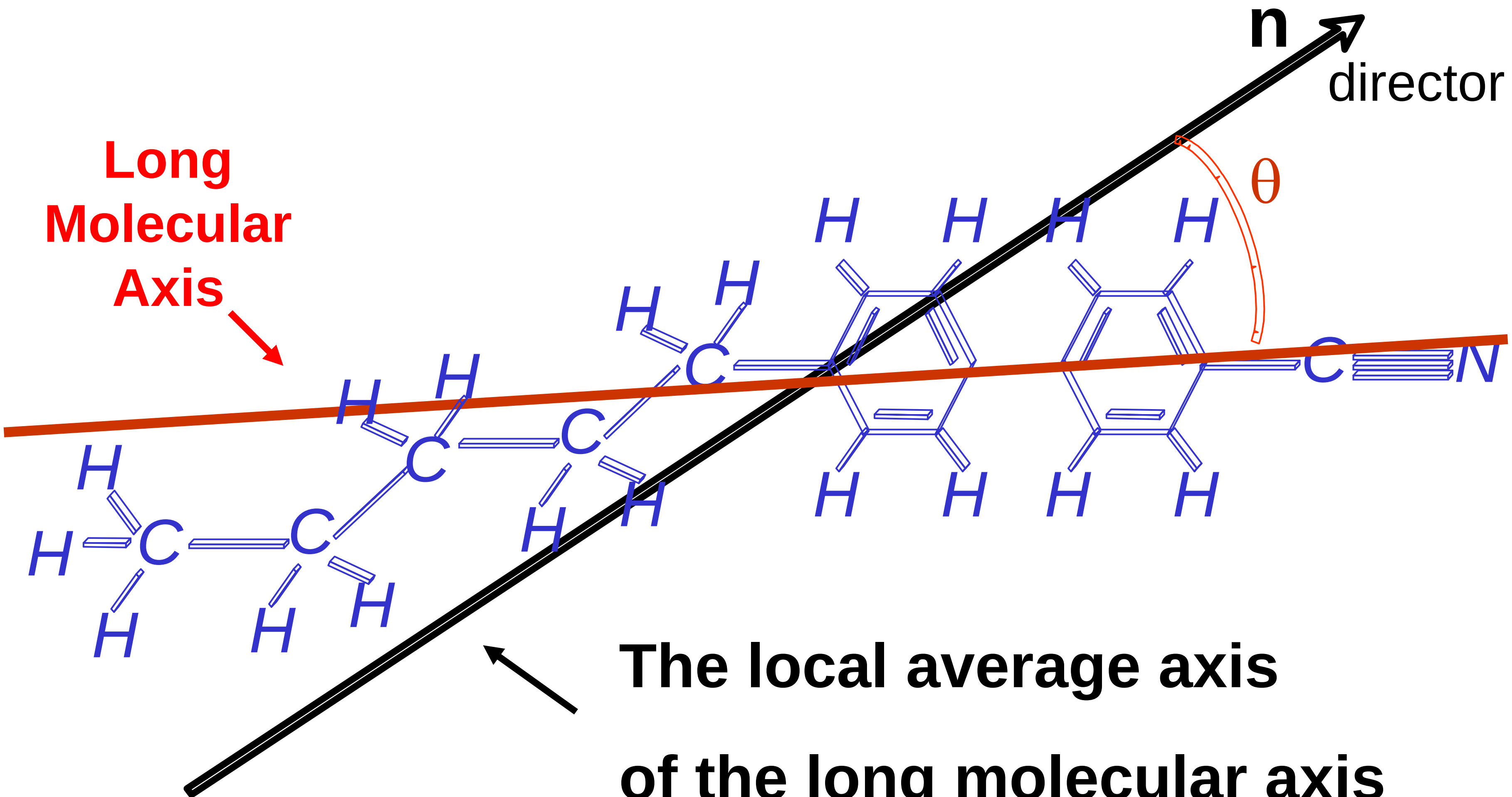
Physicist's Engineer's View



- Shape Anisotropy
- Length > Width

The molecule above (5CB) is ~2 nm × 0.5 nm

The Nematic Director n



The local average axis

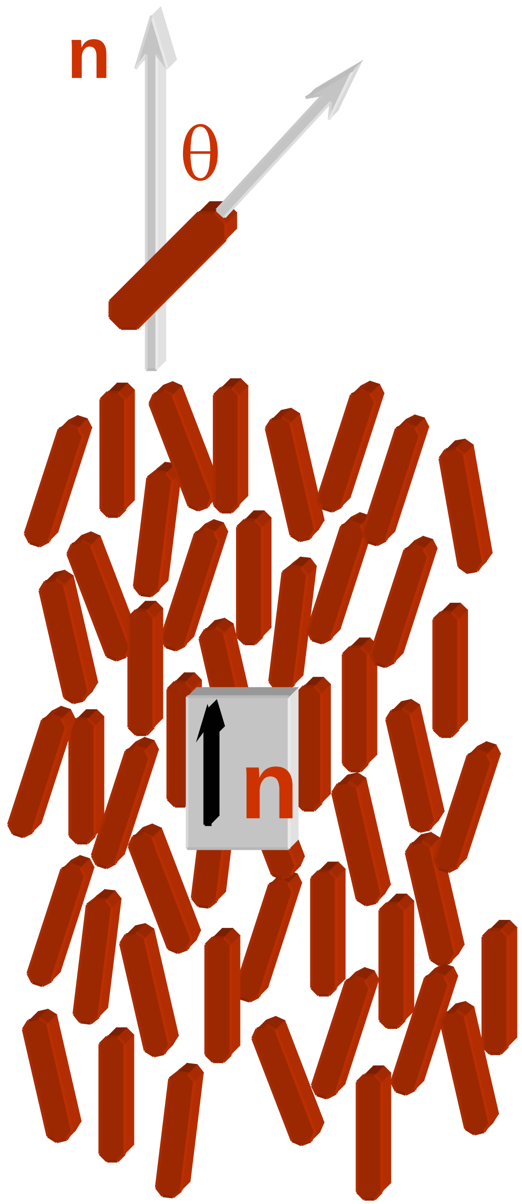
of the long molecular axis

Orientational Order of LCs

- Director **n** at any point is the preferred orientation in the immediate neighborhood
- In homogeneous LC, it is constant throughout medium
- In inhomogeneous medium, **n**=**n**(x,y,z)
- Order parameter of an LC is given by

$$S = \langle P_2(\cos\theta)\rangle = \frac{1}{2}(3\langle\cos^2\theta\rangle - 1)$$

θ is the angle between the long axis and director **n**



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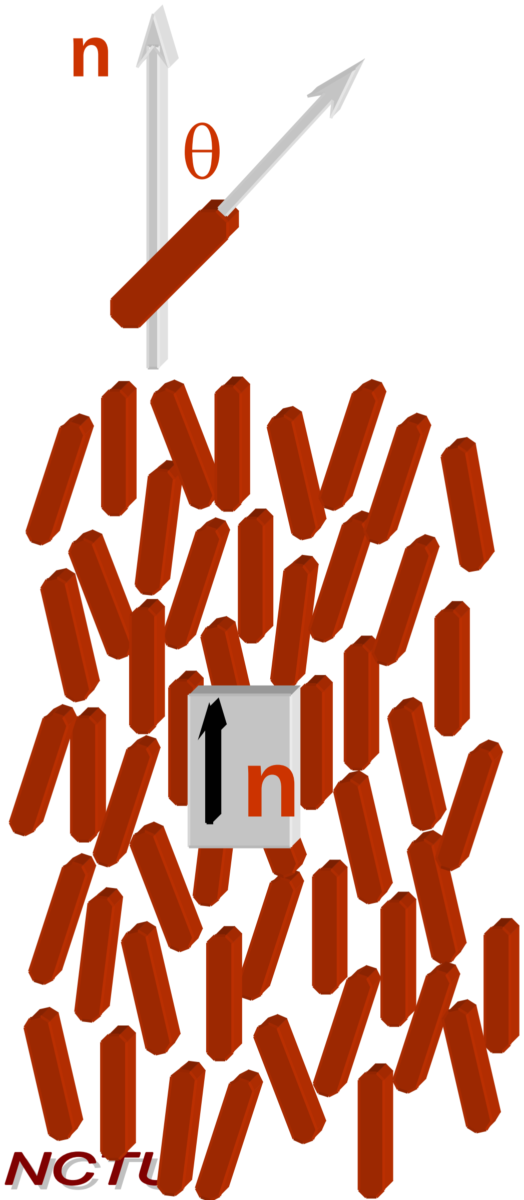
More on the Order Parameter



$$S = \left\langle P_2(\cos\theta)\right\rangle = \frac{1}{2}\left(3\left\langle \cos^2\theta\right\rangle - 1\right)$$

$$\left\langle \cos^2\theta\right\rangle = \frac{\int_\Omega \cos^2\theta d\Omega}{\int_\Omega d\Omega} = \frac{1}{3}$$ no order

$$\left\langle \cos^2(\theta = 0^o)\right\rangle = 1$$ perfect order

$$S = \left\langle P_2(\cos\theta)\right\rangle = 1$$ perfect crystal

$$S = \left\langle P_2(\cos\theta)\right\rangle = 0$$ isotropic fluid

Effects of Order Parameter

The order parameter, S, is proportional to a number of important parameters which dictate LC device performance.

Elastic Constants:	$k_{ii} \propto S^2$
Dielectric Anisotrophy	$\Delta\varepsilon \propto S$
Birefringence	$\Delta n \propto S$
Magnetic Anisotrophy	$\Delta\chi \propto S$
Viscosity Anisotrophy	$\Delta\eta \propto S$

$$V_{th} \propto \sqrt{\frac{K}{\Delta\varepsilon}} \propto \sqrt{\frac{S^2}{S}} = \sqrt{S}$$

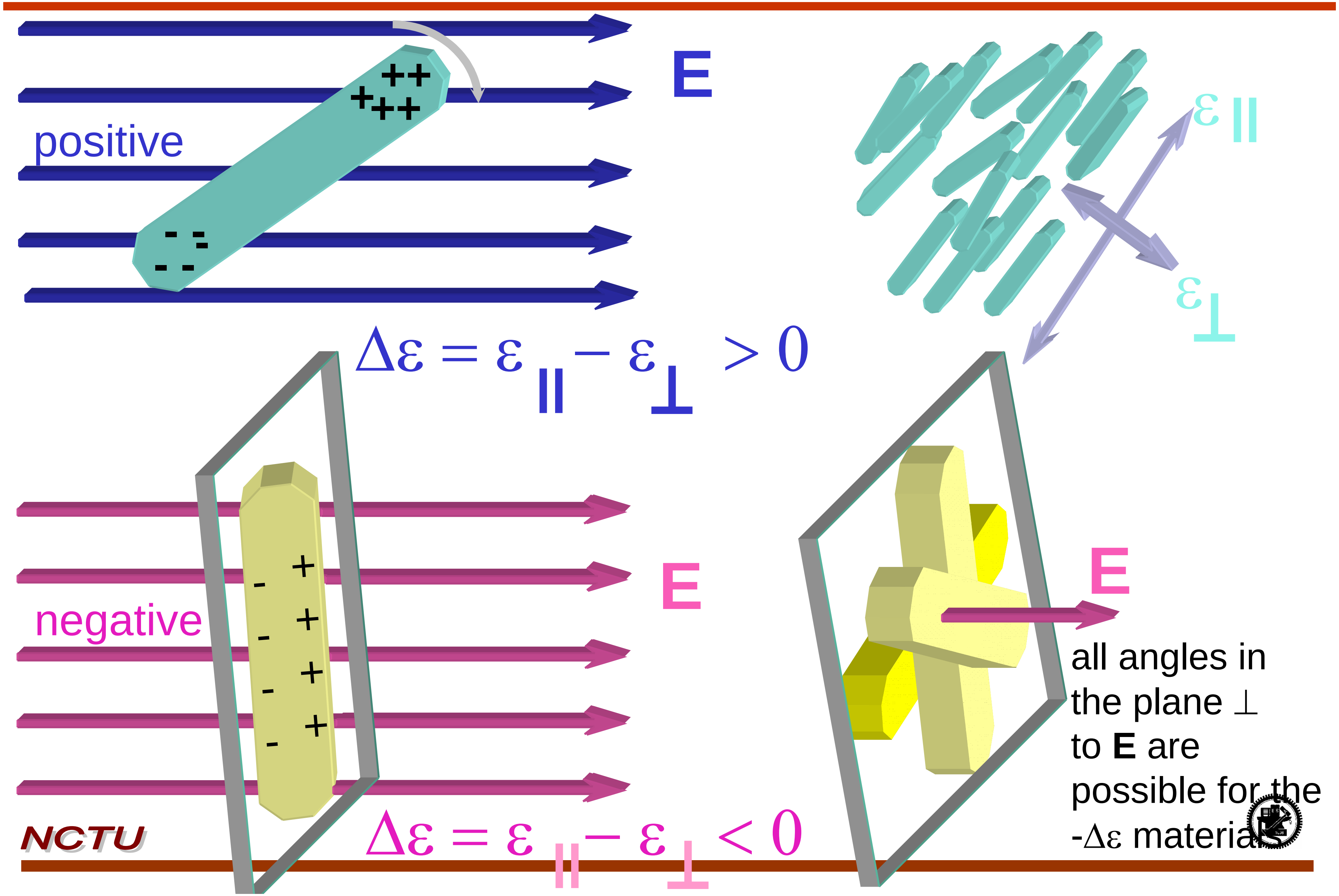
Dielectric Constants

- Nematic and smectic LCs are uniaxially symmetric with axis of symmetry parallel to the director **n**
  - Dielectric constants differ in value along the preferred axis ($\varepsilon_{//}$) and perpendicular to the preferred axis ($\varepsilon_{\perp}$)
  - Dielectric anisotropy is $\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$, $-2\varepsilon_o \le \Delta\varepsilon \le 15\ \varepsilon_o$
- The macroscopic energy is: $W_{em} = \frac{1}{2}\vec{D}.\vec{E}$
- If θ is the angle between the director and z-axis

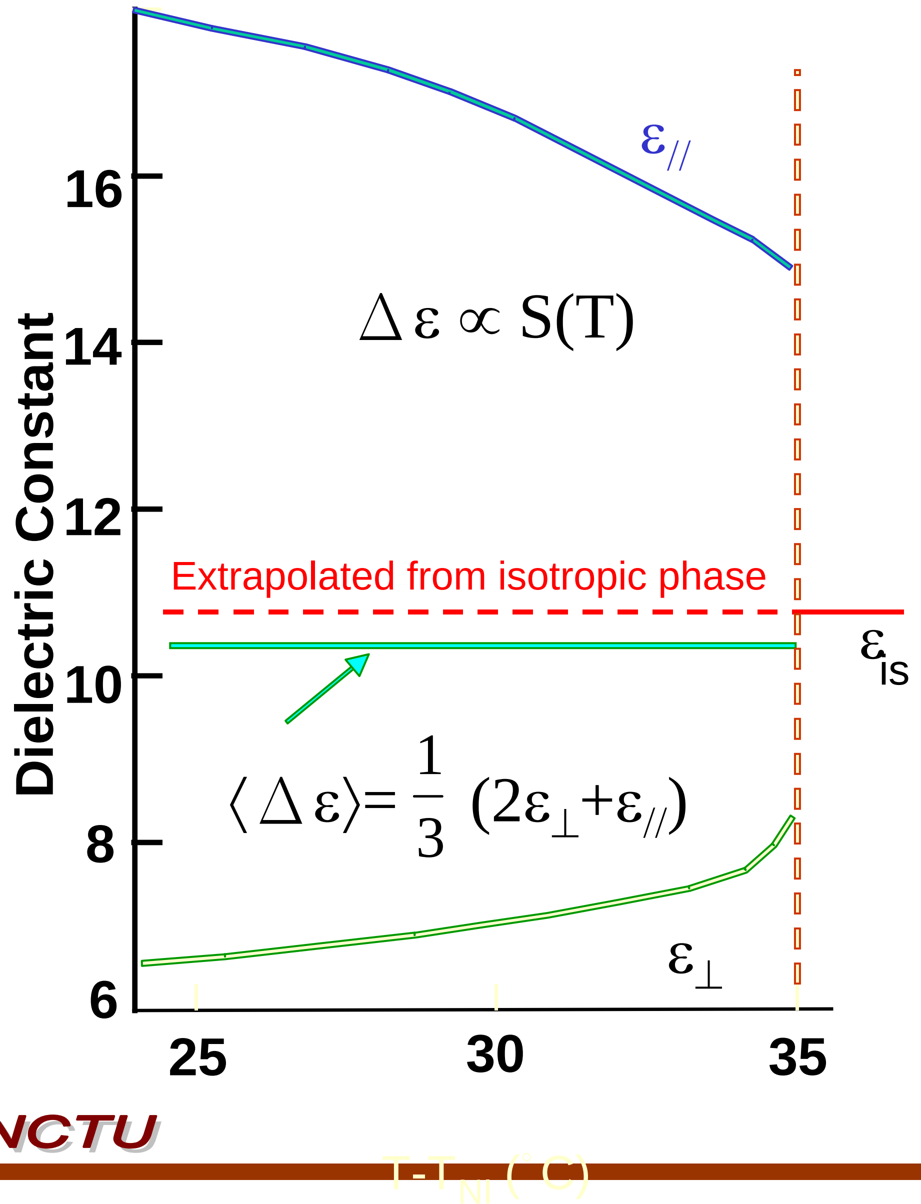
$$D_z = (\varepsilon_{//}\cos^2\theta + \varepsilon_{\perp}\sin^2\theta)E$$

$$W_{em} = \frac{1}{2}\frac{D_z^2}{\varepsilon_{//}\cos^2\theta + \varepsilon_{\perp}\sin^2\theta}$$

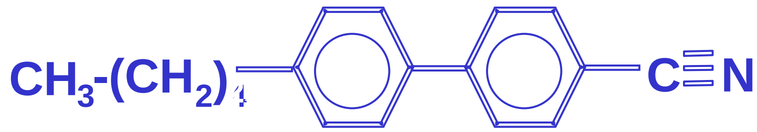
Anisotropy: Dielectric Constant



Dielectric Constants: Temperature Dependence



4'-pentyl-4-cyanobiphenyl



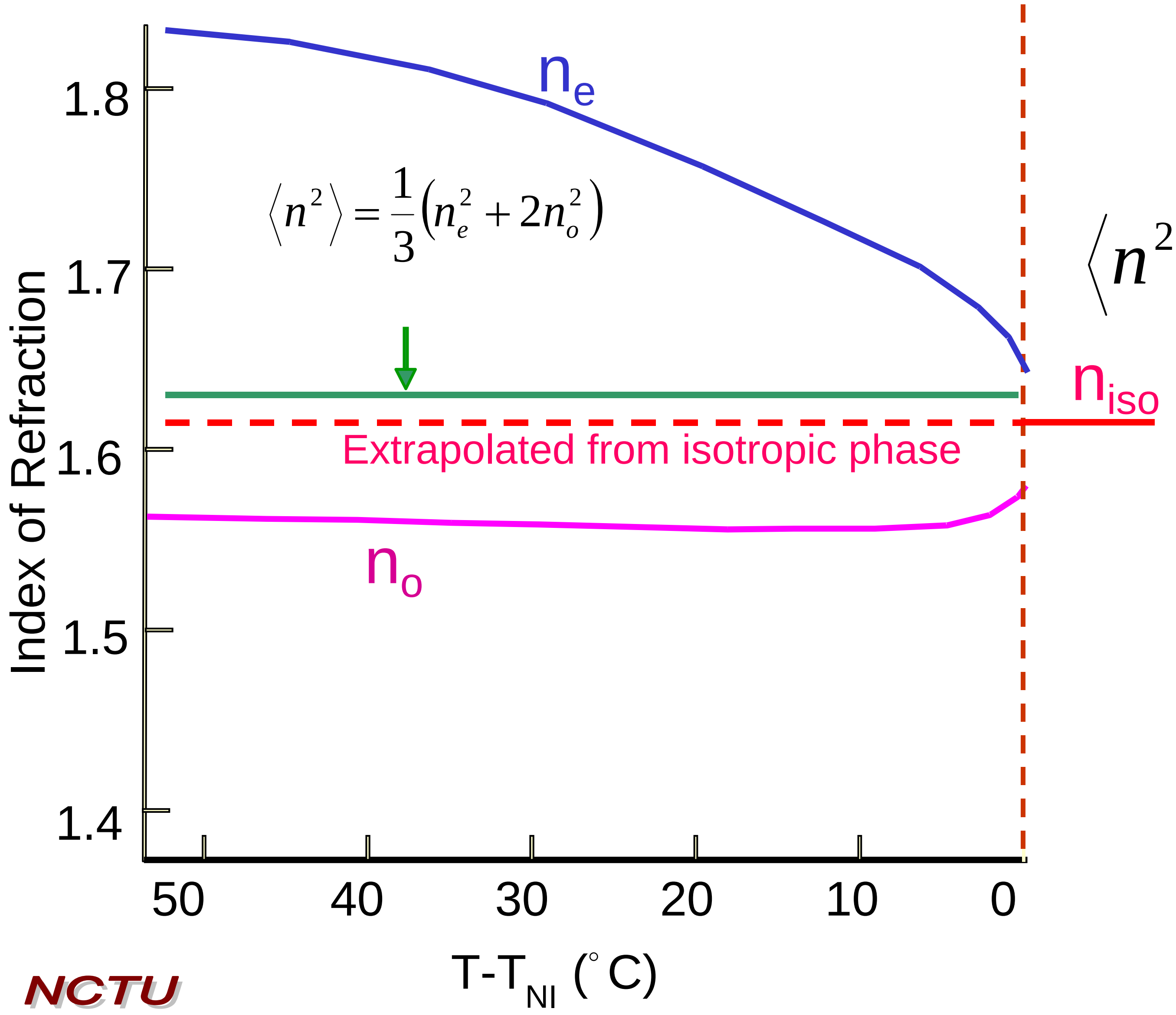
Temperature Dependence

$$\Delta\varepsilon \propto S(T)$$

Average Dielectric Anistropy

$$\langle \Delta\varepsilon \rangle = \frac{1}{3}(2\varepsilon_{\perp} + \varepsilon_{//})$$

n_e and n_o: Temperature Dependence



Average Index

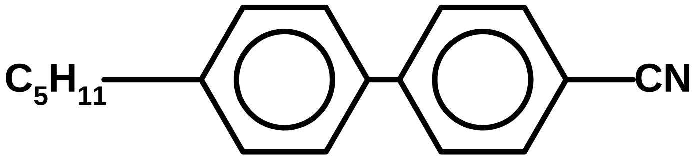
$$\langle n^2 \rangle = \frac{1}{3}\left(n_e^2 + 2n_o^2\right)$$

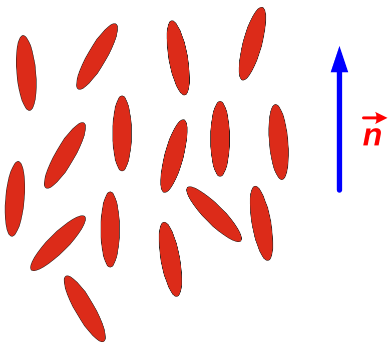
Temperature Dependence

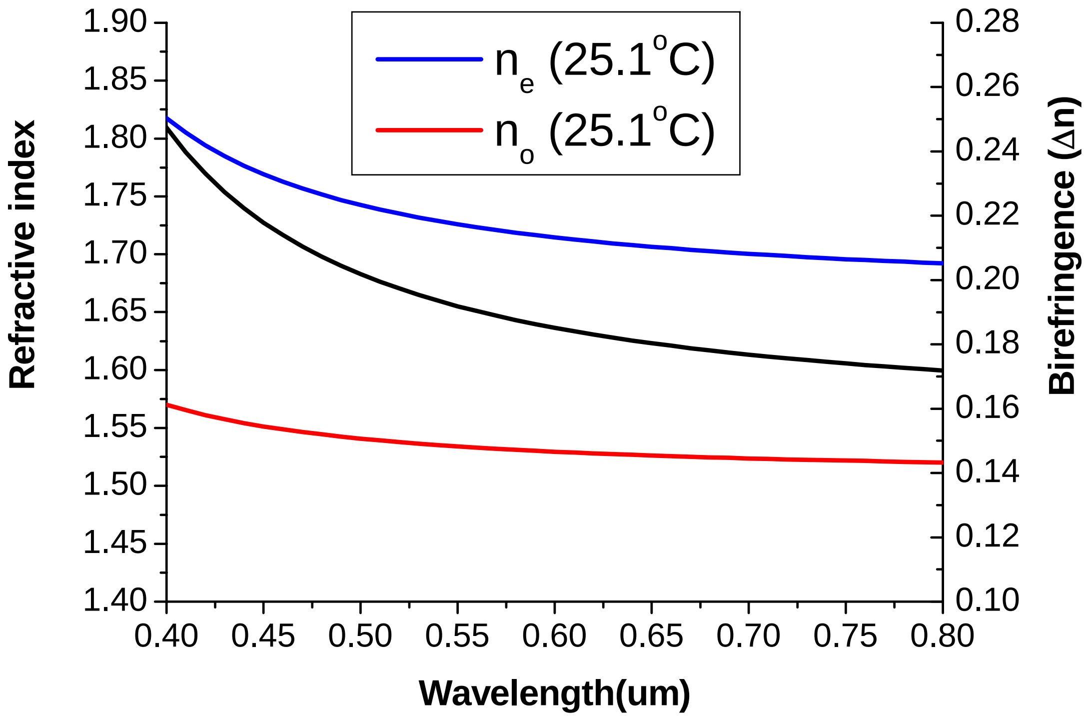
$$\Delta n \propto S(T)$$

5CB: a typical NLC

•5CB (K15): 4'-*n*-pentyl-4-cyanobiphenyl







Nematic phase

***T* = 22.4 °C ---- 34.5 °C**

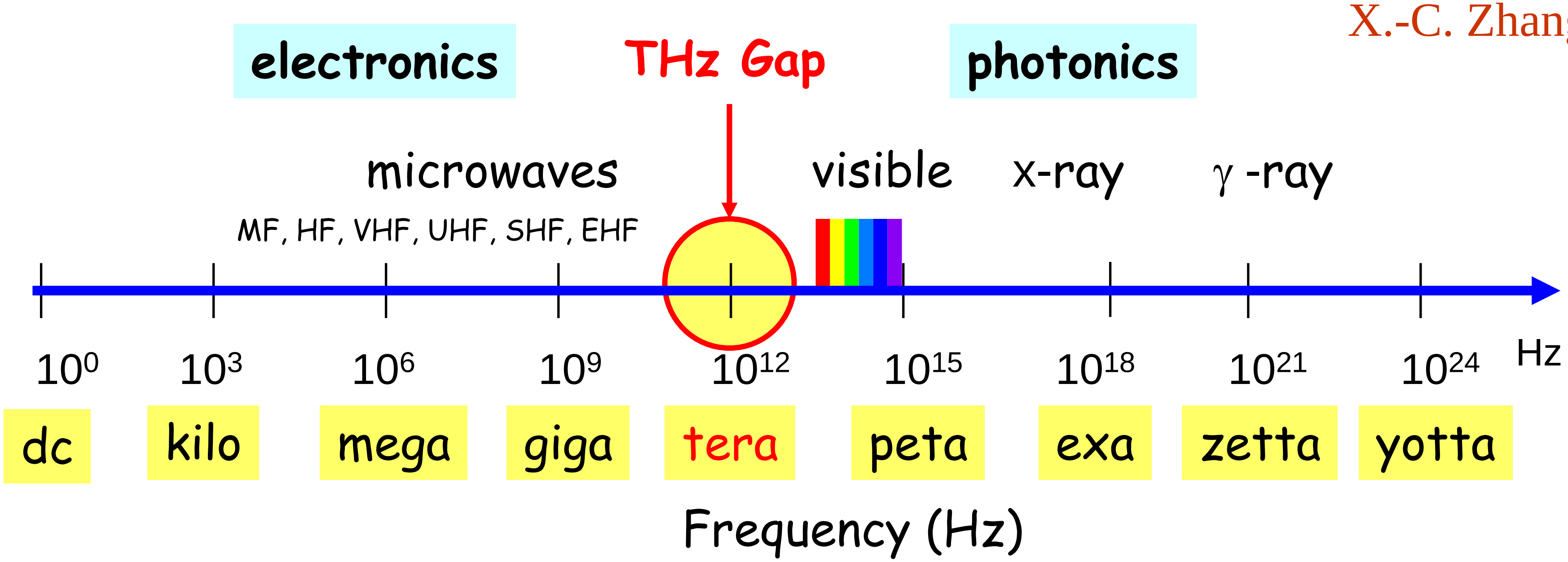
In the visible,

Δn (λ ,T)=n_e-n_o=*0.14~0.19*

T-Ray: Next frontier in Science and Technology

Terahertz wave (or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz, lies a frequency range with rich science but limited technology.

Courtesy of X.-C. Zhang



1 THz ~ 1 ps ~ 300 μm ~ 33 cm^{-1} ~ 4.1 meV ~ 47.6 °K

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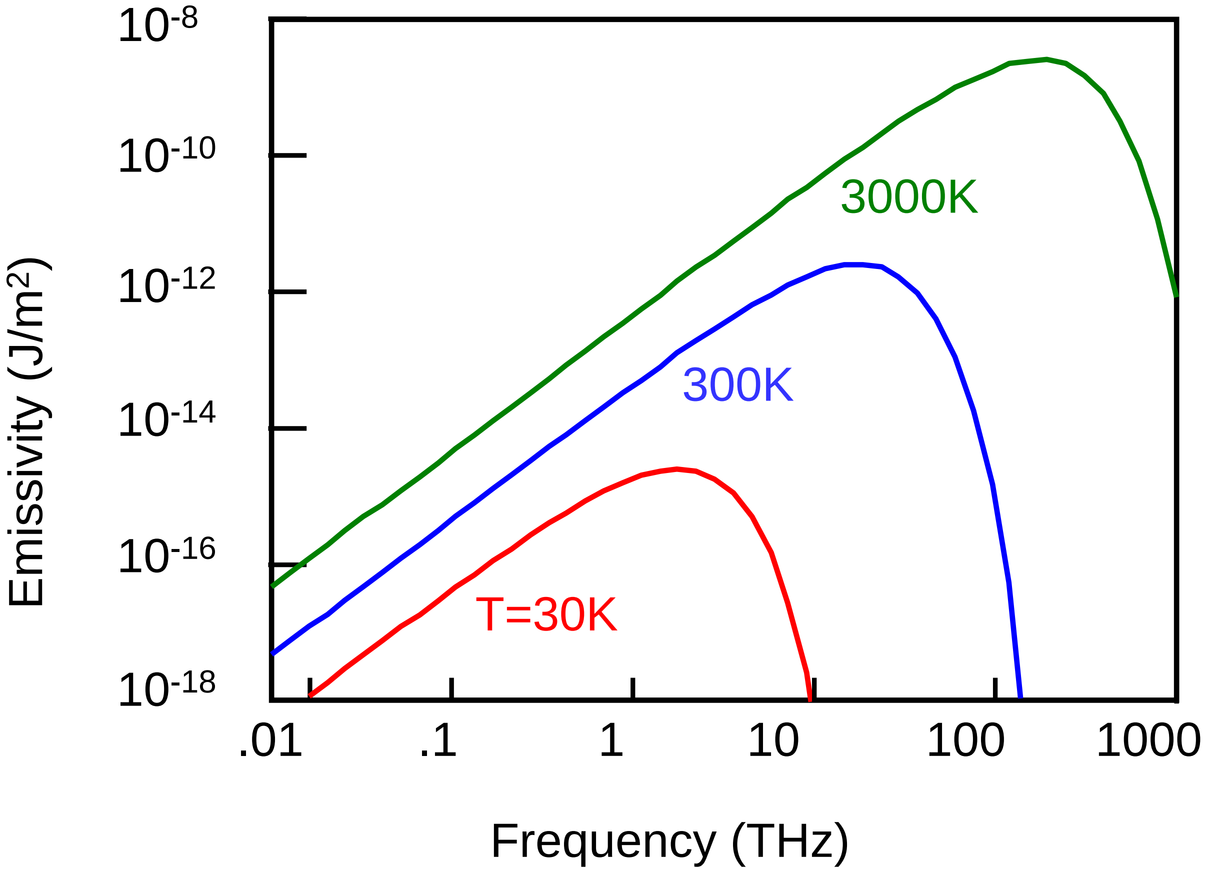
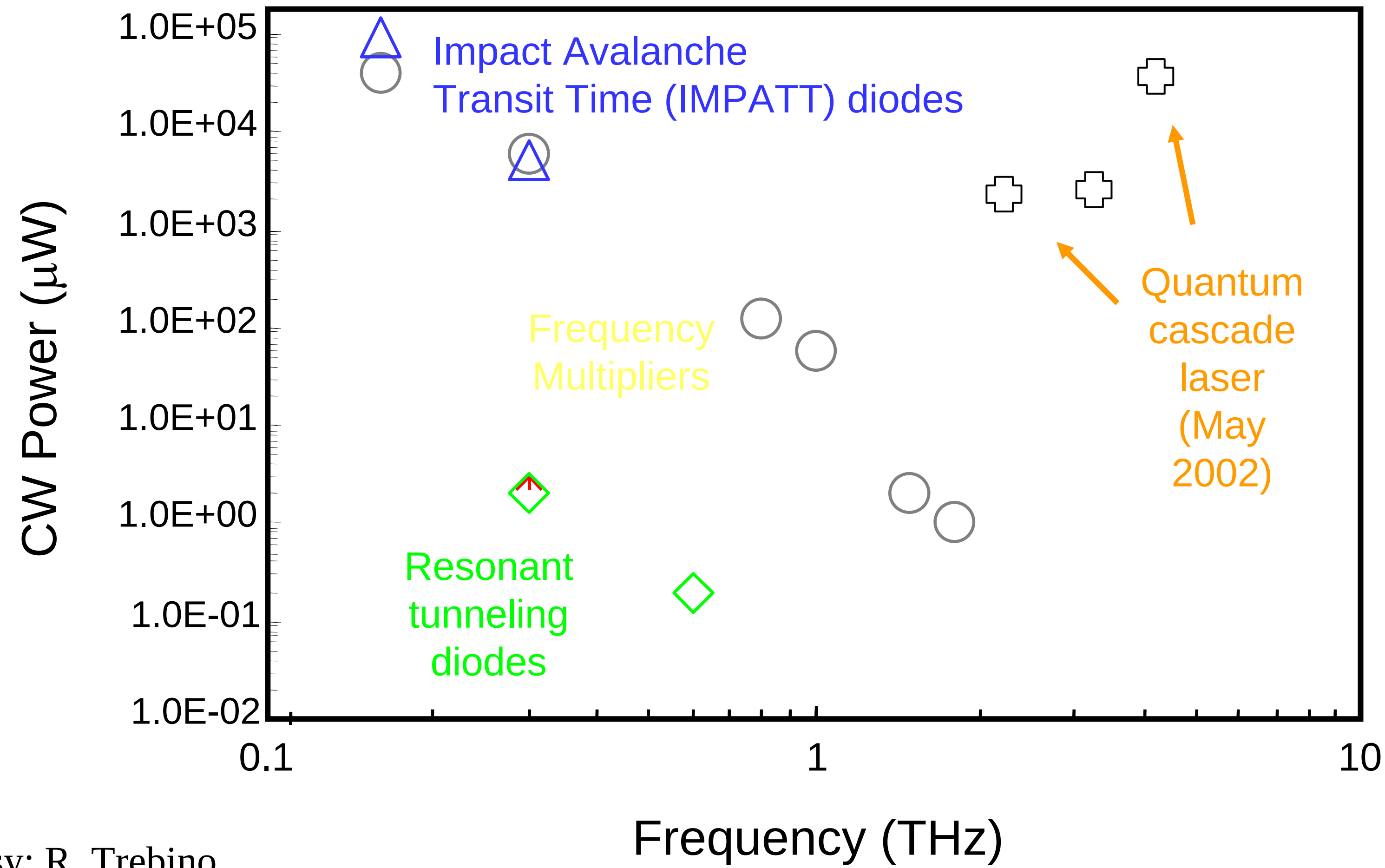
Blackbody Radiation: Natural Source of THz Radiation



Natural sources of THz are very weak.

"Traditional" electronic approaches to "THz light"



Courtesy: R. Trebino

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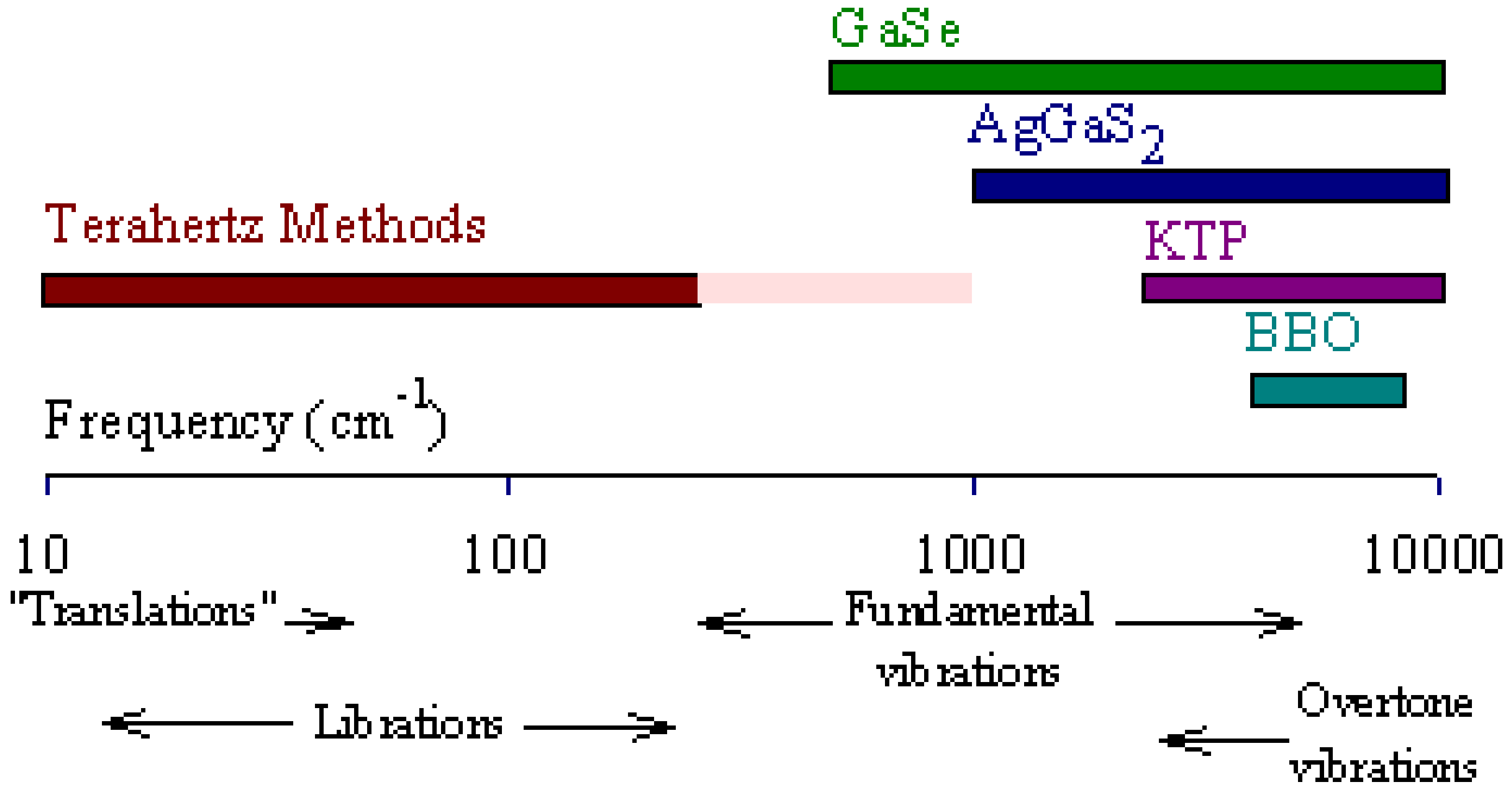
Peter Siegel, JPL

THz and Optical Parametric Generators

THz picks up where OPG's leave off.

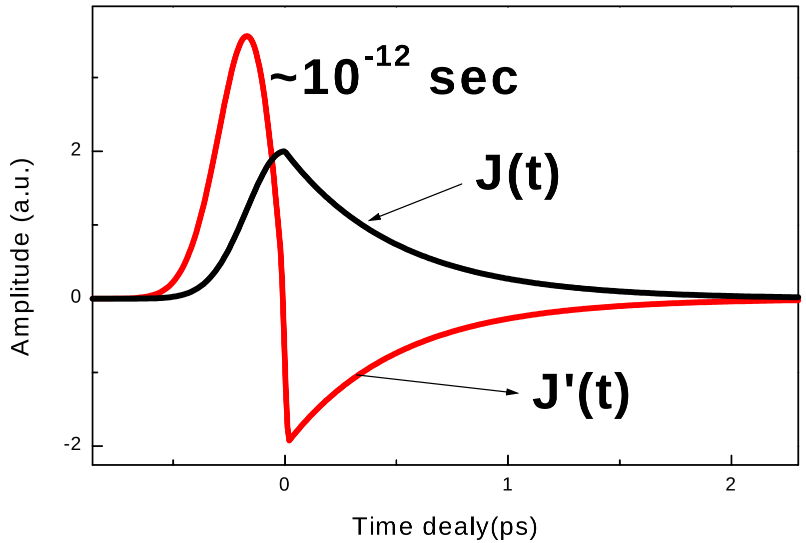


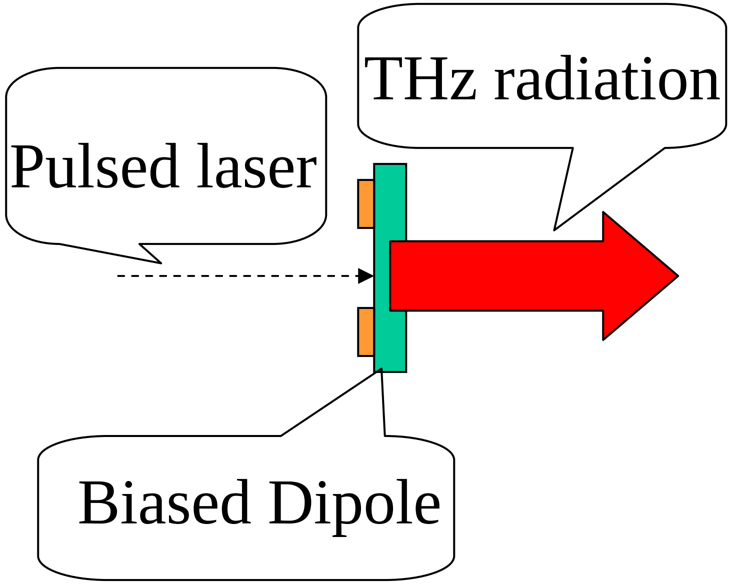
Generation of THz Wave: current surge effect

- **Hertzian dipole antenna in free space.**

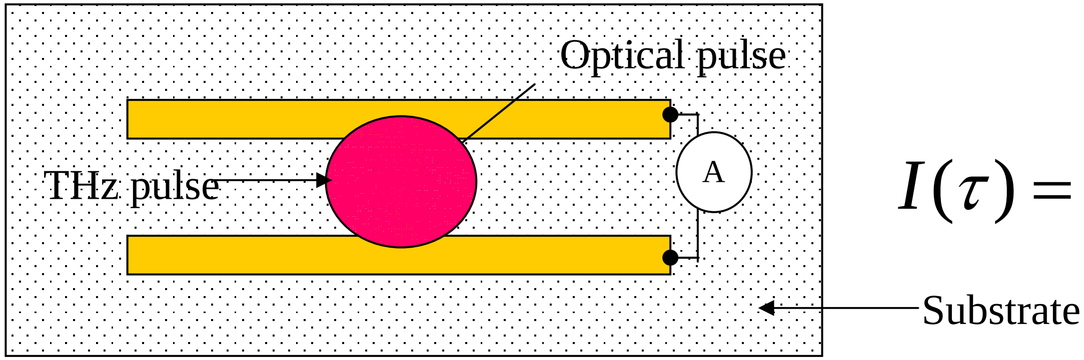
$$J(t) = n(t)e\mu E_b$$

$$E(r,t) \propto \frac{1}{r}\frac{\partial J(t)}{\partial t}$$





Detection of THz Wave: Photoconductive Antenna



$$I(\tau) = e\mu\tau_c m\int_{t_1}^{t_2} E(t)n(t-\tau)dt$$

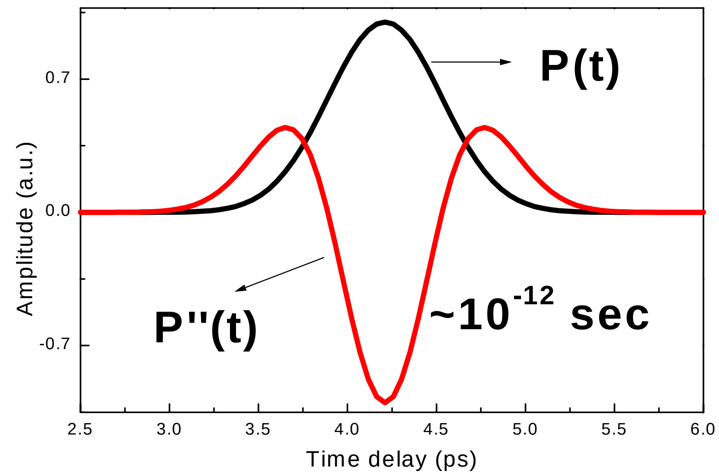
I(τ): detected signal current, e: electron charge, μ: carrier mobility, τ_c: carrier life time, m: repetition rate, τ: relative time delay between THz pulse and gating laser pulse, n(t): photo-induced transient carrier density, E(t): THz field.

Substrate with

- Shorter carrier life time: n(t)~delta function =>$E(t)\propto I(t)$
- Long carrier life time: n(t)~step function=>$E(t)\propto dI(t)/dt$

Generation of THz Wave: Optical rectification

- Transient polarization generated after pulse laser (wide band width) excited optical nonlinear materials
- Transient polarization:



$$P(\Omega) = \chi^{(2)}(\Omega, \omega+\Omega, -\omega) E(\omega+\Omega) E^*(\omega)$$

$$P(\Omega) = \chi^{(3)}(\Omega, \omega+\Omega, -\omega, 0) E(\omega+\Omega) E^*(\omega) E_{dc}(0)$$

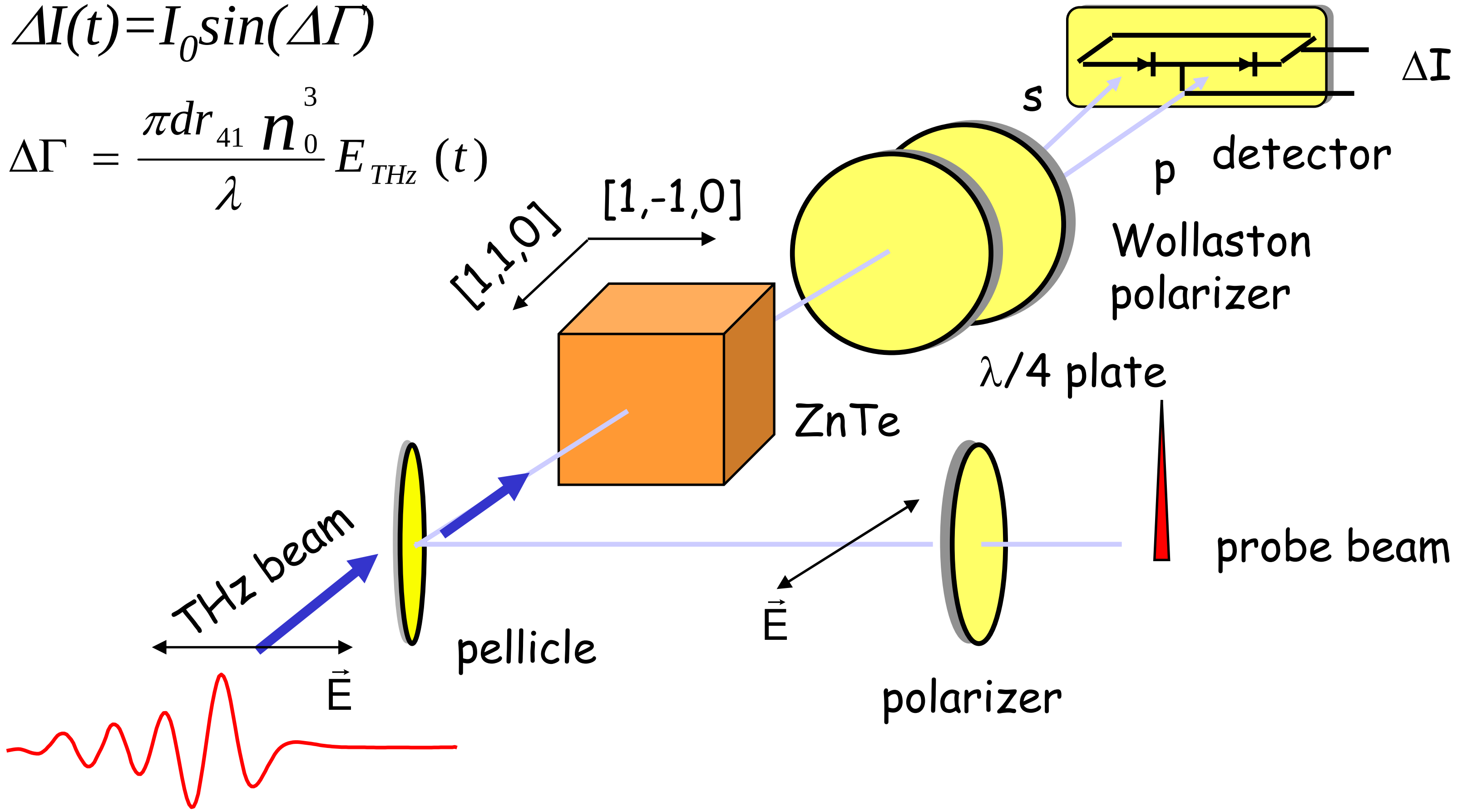
- Radiated THz field:

$$\vec{E}_r \propto \frac{\partial}{\partial t} \vec{J}(t) \propto \frac{\partial^2}{\partial t^2} \vec{P}(t)$$

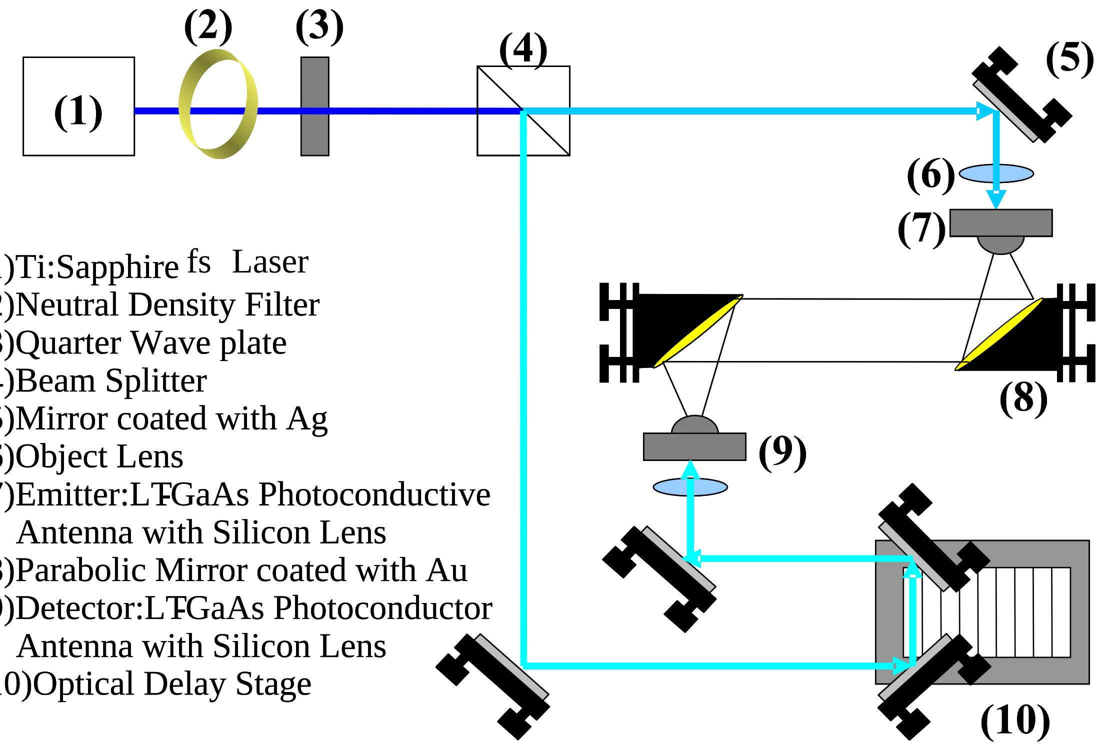
Detection of THz Wave:
Electro-Optic Sampling

$$\Delta I(t)=I_0 \sin(\Delta\Gamma)$$

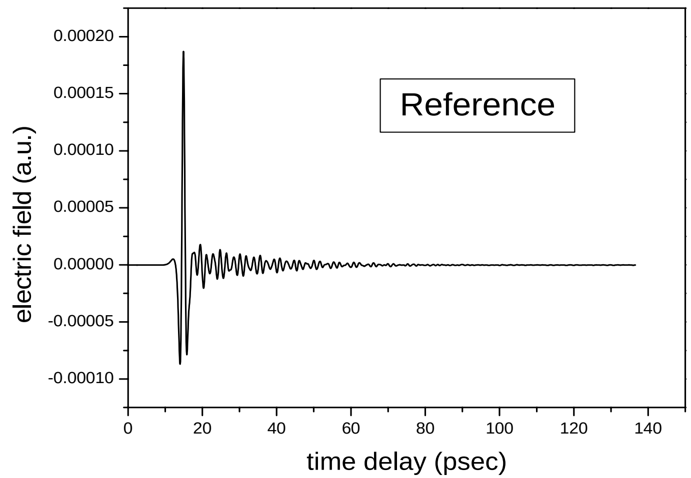
$$\Delta\Gamma = \frac{\pi d r_{41} n_0^3}{\lambda} E_{THz}(t)$$



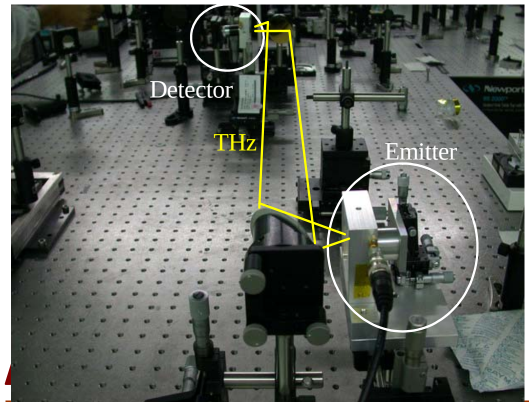
Terahertz Time-Domain Spectroscopy (THz-TDS)



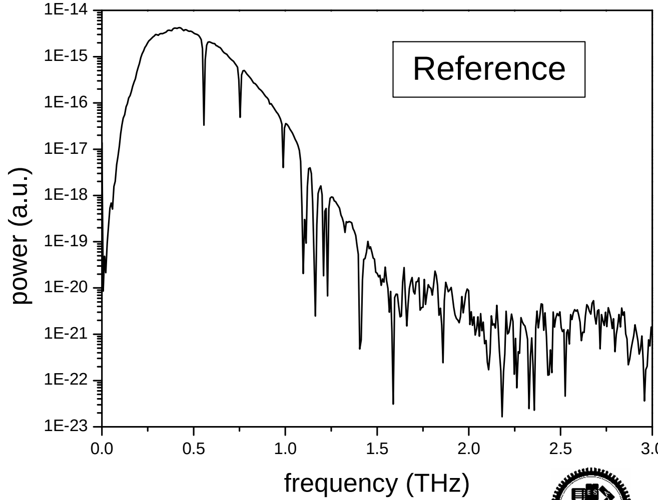
(1)Ti:Sapphire fs Laser
(2)Neutral Density Filter
(3)Quarter Wave plate
(4)Beam Splitter
(5)Mirror coated with Ag
(6)Object Lens
(7)Emitter:LT-GaAs Photoconductive Antenna with Silicon Lens
(8)Parabolic Mirror coated with Au
(9)Detector:LT-GaAs Photoconductor Antenna with Silicon Lens
(10)Optical Delay Stage



Free space THz time domain waveform

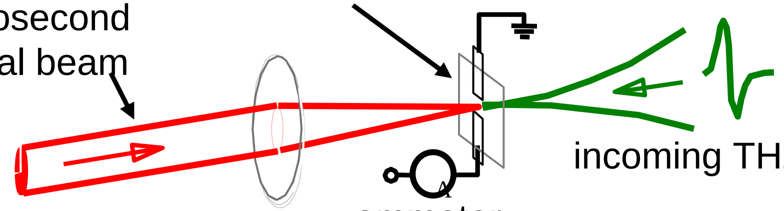


•The emitter and detector using small gap LT-GaAs photoconductive antenna
•The signal to noise ratio is up to million
•The bandwidth is between 0.1 to 1.5 THz

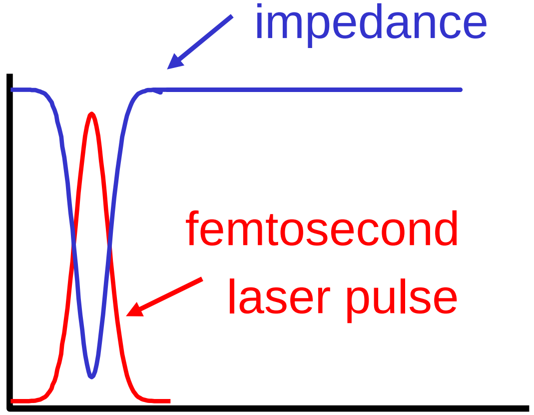


THz frequency domain spectrum

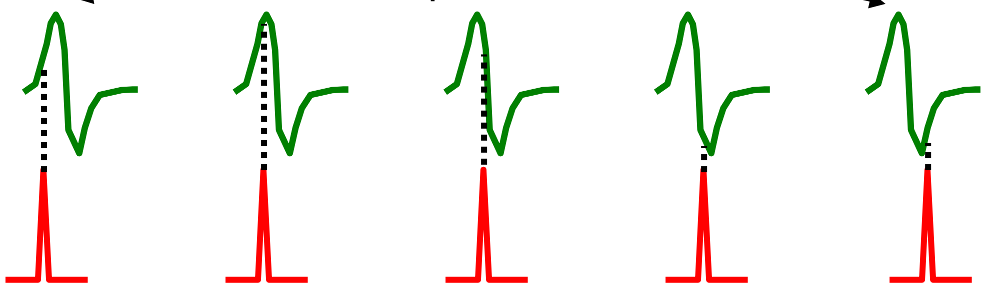
Measuring THz pulses using photoconductive sampling



Antenna impedance vs. time



Scanning the delay is performed as in cross-correlation.

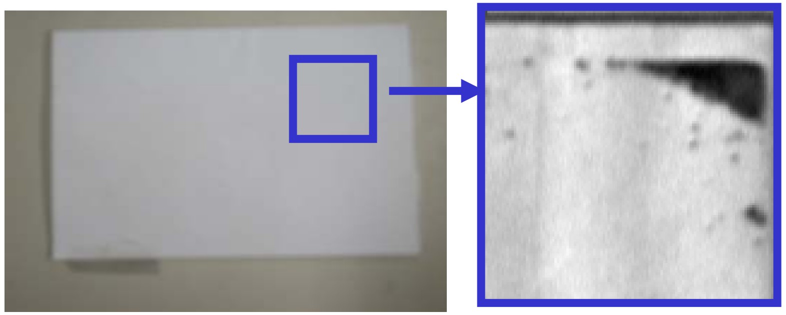


Because the fs optical pulse is shorter than the THz pulse, this works.

THz Imaging: Examples

1. 兆赫輻射可以清楚的看到鈔票上的浮水印

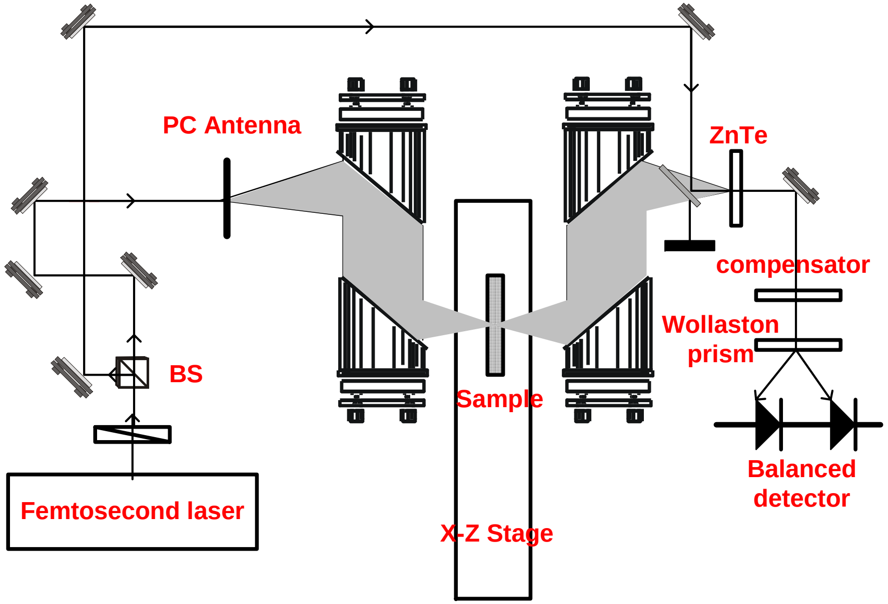
2. 兆赫輻射可以檢測出信封裡面的粉末分布未來有可能應用於生物戰劑如碳疽桿菌之檢測）



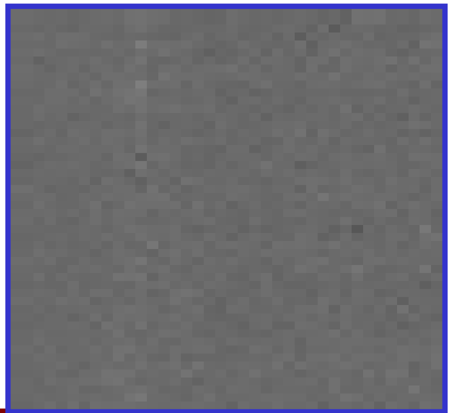
優點及應用：

- 對人體安全
- 非接觸性
- 極佳的訊噪比
- 可應用於反恐、醫學組織診斷、 食物檢測、化學成分分析、材料特性分析

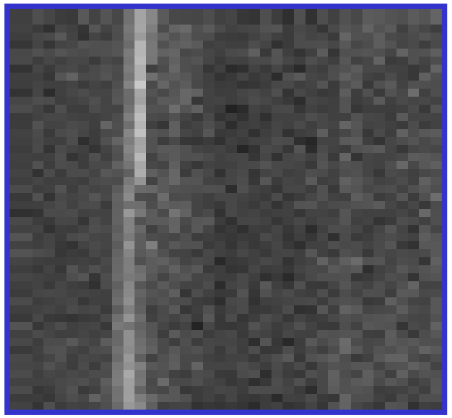
THz Movie of a Match Box



time domain (amplitude)



frequency domain (amplitude)



phase

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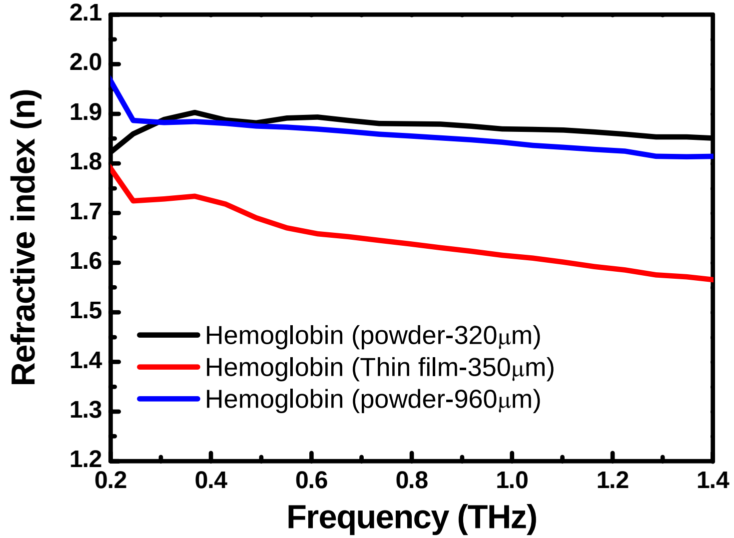
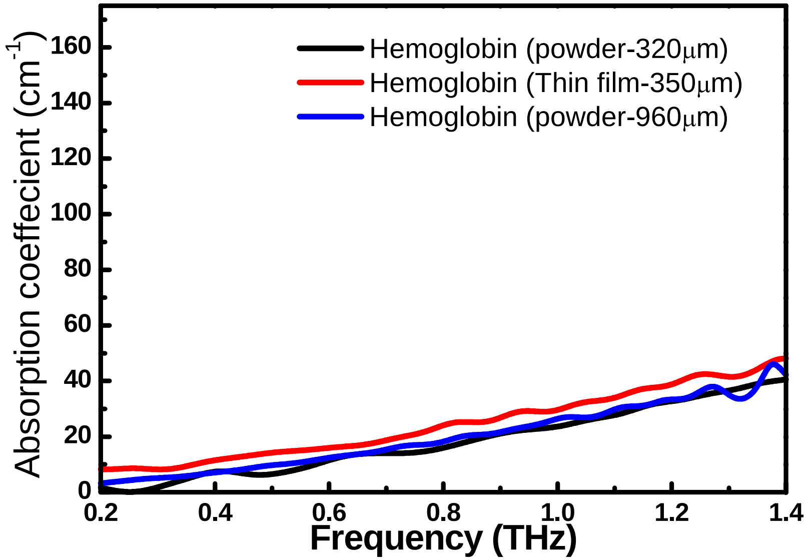
THz Biomedical Sensing:

Refractive index and absorption coefficient of deoxyhemoglobin

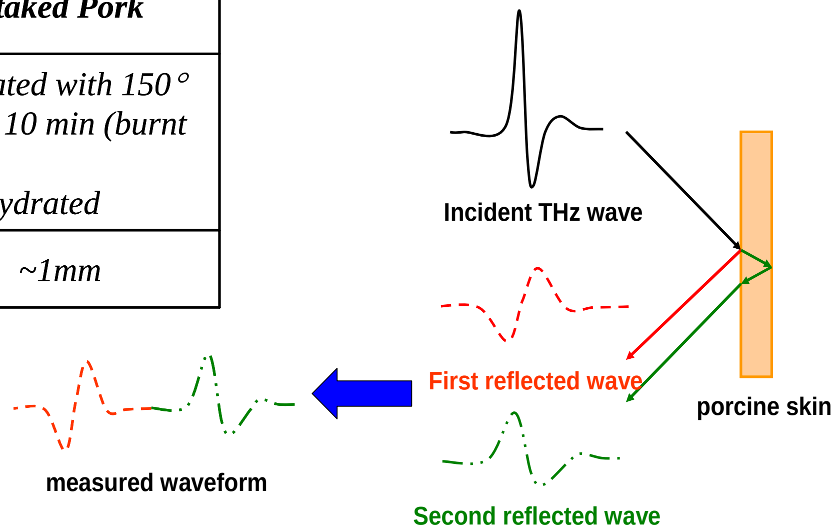


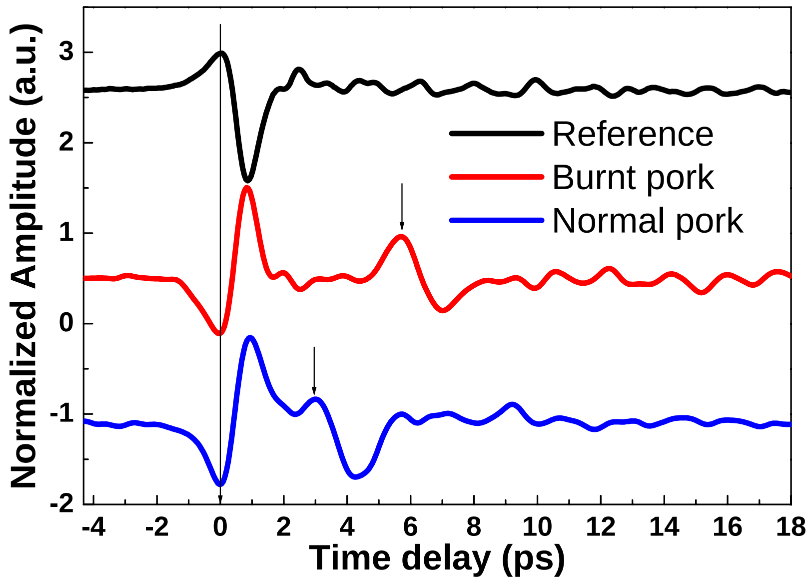


	Water	Blood	Hemoglobin (powder)	Hemoglobin (Thin film)
Refractive index- mean value (with standard deviation)	~2.04 (0.07)	~2.01 (0.03)	~1.87 (0.02)	~1.61 (0.03)
Absorption coefficient (cm^{-1})	150➔250	120➔240	8➔46	14➔52

Burn-depth detection of pork with T-ray technology (I)

Type	*Normal Pork*	*Burnt Pork*	*Staked Pork*
Preparation process	*Dehydrated*	*1. Heated with 150 ° C for 10 min 2.Dehydrated*	*1. Heated with 150 ° C for 10 min (burnt part) 2.Dehydrated*
Thickness	*0.27mm*	*0.533mm*	*~1mm*





	d (thickness, mm)	T (time of flight, ps)	n (refractive index)
Normal	0.27	3.01	1.67
Burnt	0.533	6.18	1.74

Refractive index of burnt and normal porcine is determined via THz time of flight

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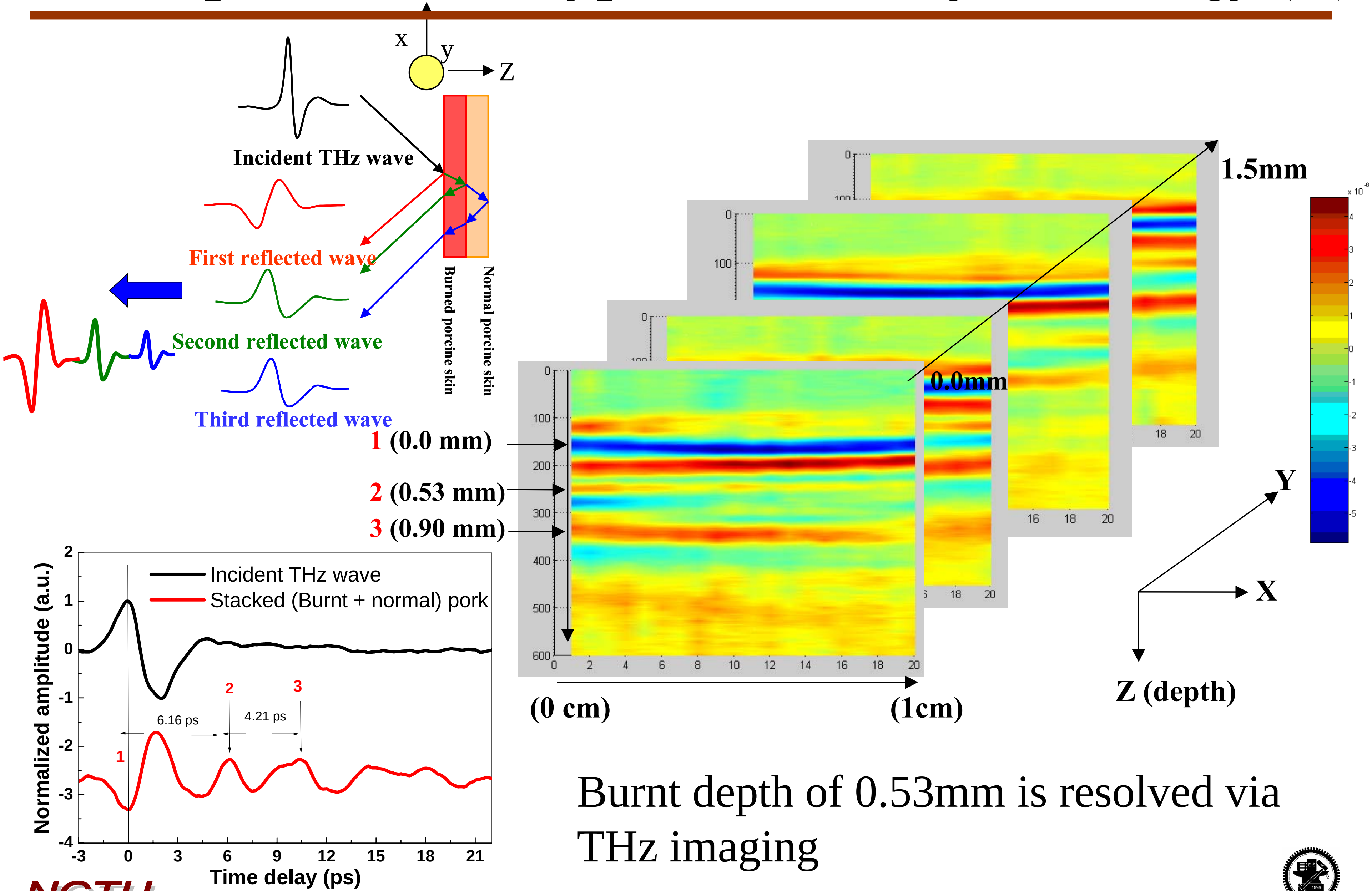
Burn-depth detection of pork with T-ray technology (II)



Burnt depth of 0.53mm is resolved via THz imaging

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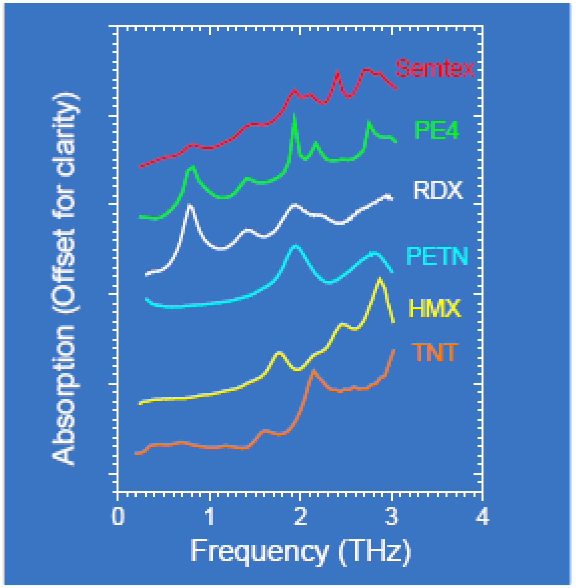
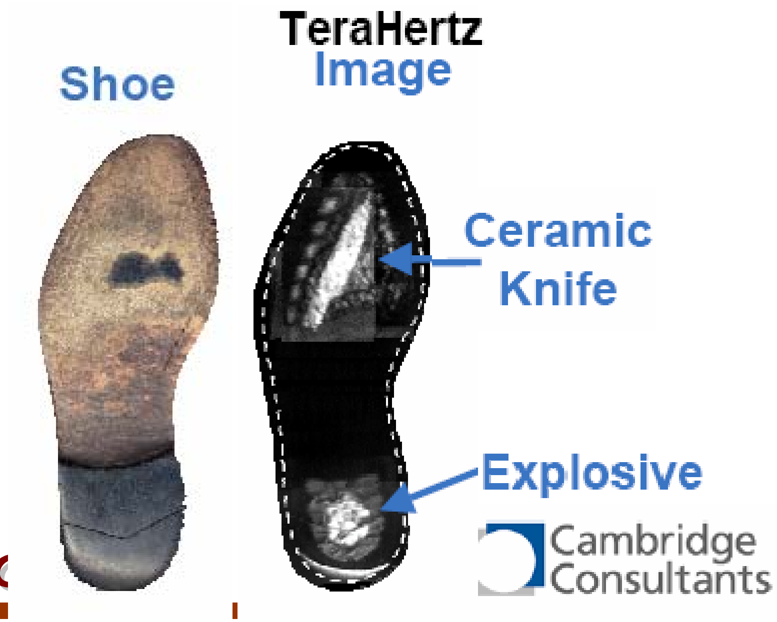
Homeland Security

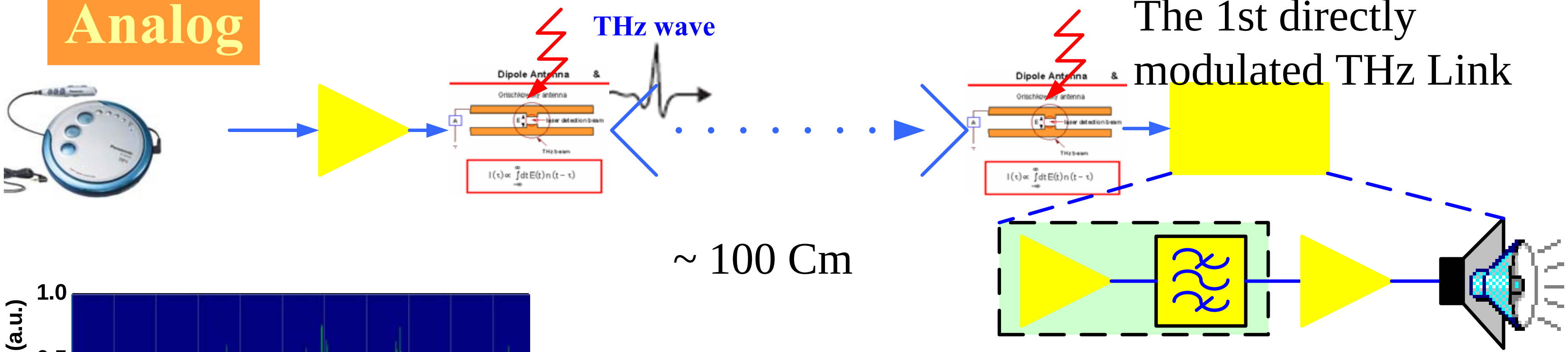


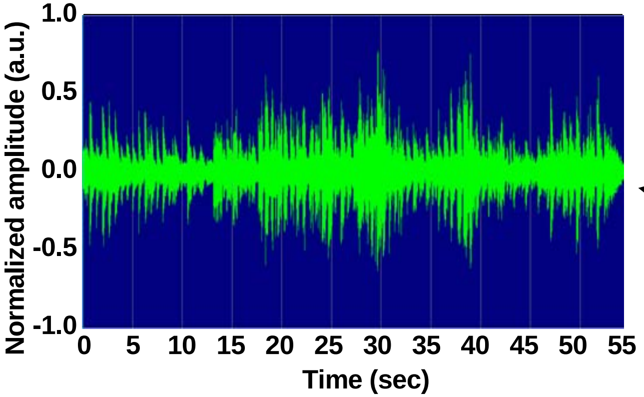


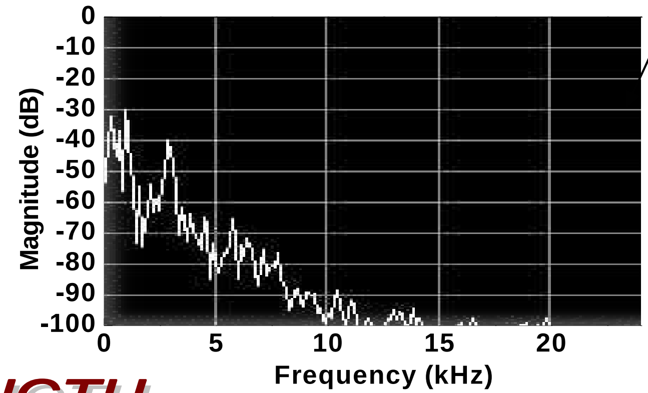
Towards THz Communication Link

Analog

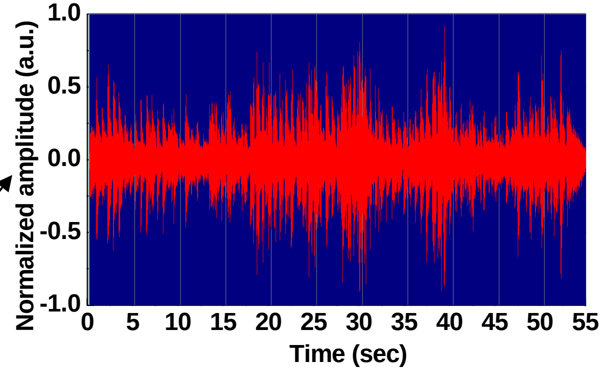
The 1st directly modulated THz Link

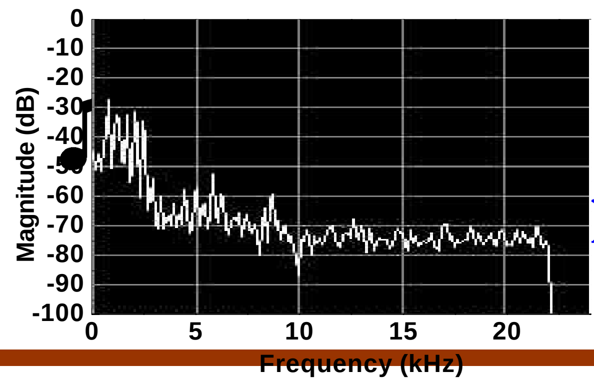






Original music time sequence and a portion of spectrum



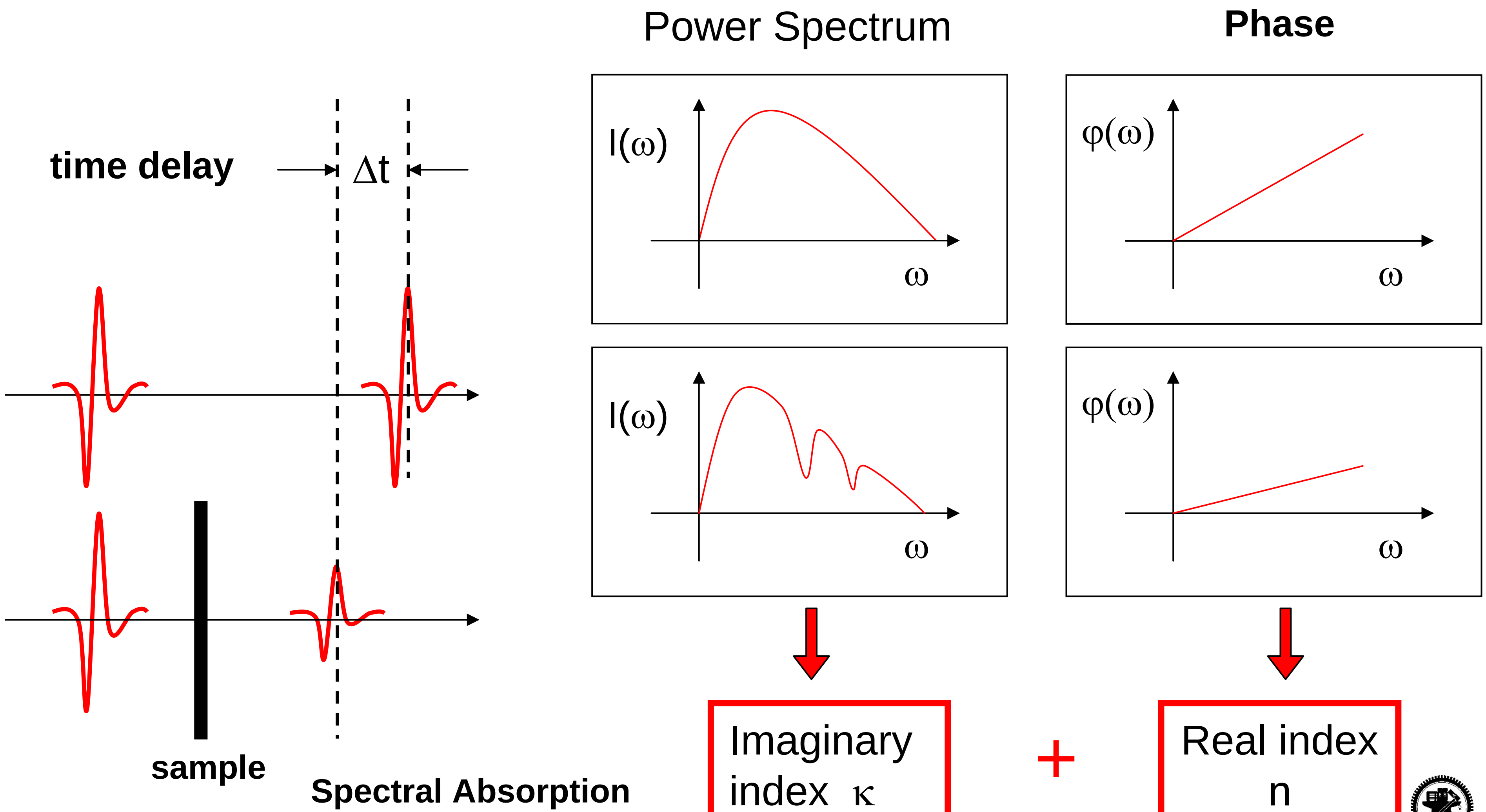


Received music time sequence and a portion of spectrum

NCTU

Opt. Exp.,Dec’05

THz-TDS: Extraction of Far IR Optical Constants of Materials



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How to derive n and k from THz-TDS (I)

time-domain waveforms

⬇ **FFT**

frequency-domain data

⬇

Transmission function

$$T(\omega) = \frac{E_{SAMPLE}(\omega)}{E_{REF}(\omega)}$$

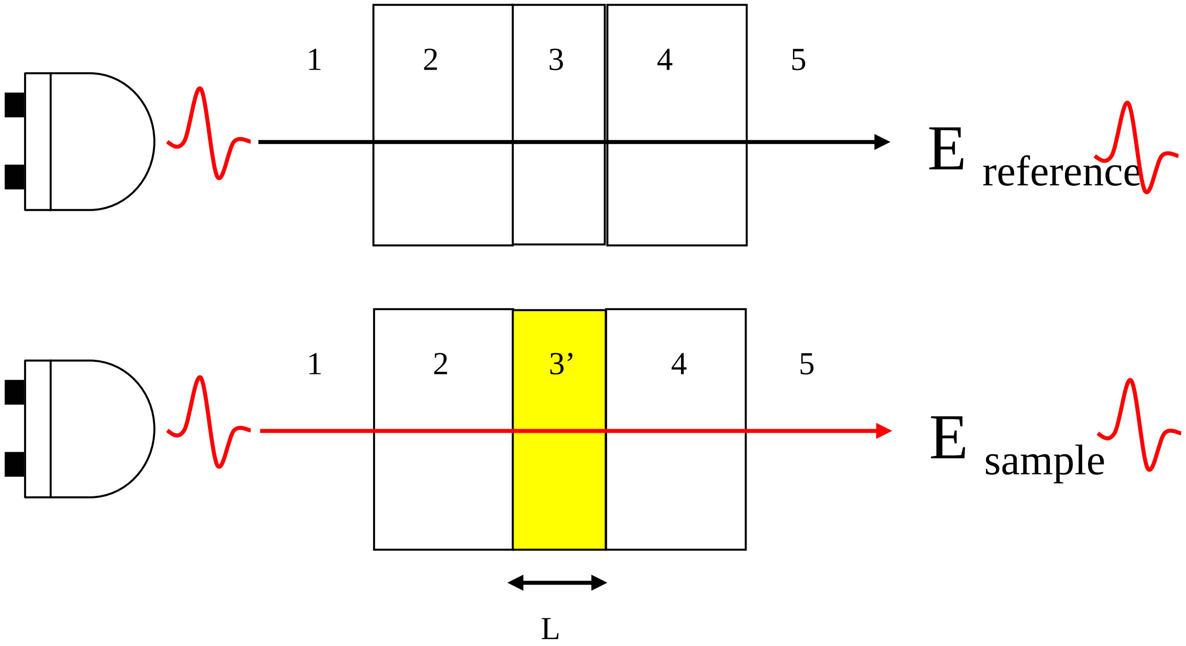
⬇

Numerical method,

(L. Duvillaret *et al*. IEEE J. Sel Top quantum Electron. 2, 739 (1996))

➡ ***n, k***

How to derive n and k from THz-TDS (II)



1: air
2: fused silica
3':sample
3: air
4: fused silica
5: air

Terms considered:

1. transmission and reflection coefficients at a-b interface;

2. propagation coefficient in medium a;

3. Fabry-Perot effect between layers 2 and 4;

a, b: 1-4

How to derive n and k from THz-TDS (III)

$$E_{reference}(\omega) = T_{12}(\omega)P_2(\omega,L)T_{23}(\omega)P_3(\omega,L)T_{34}(\omega)P_4(\omega,L)T_{45}(\omega)\bullet$$

$$\underbrace{\sum_{k=0}^{+\infty}\left[R_{34}(\omega)P_3^2(\omega,L)R_{32}(\omega)\right]^k}_{FP_3(\omega)}\bullet E(\omega)$$

$$E_{sample}(\omega) = T_{12}(\omega)P_2(\omega,L)T_{23'}(\omega)P_{3'}(\omega,L)T_{3'4}(\omega)P_4(\omega,L)T_{45}(\omega)\bullet$$

$$\underbrace{\sum_{k=0}^{+\infty}\left[R_{3'4}(\omega)P_{3'}^2(\omega,L)R_{3'2}(\omega)\right]^k}_{FP_{3'}(\omega)}\bullet E(\omega)$$

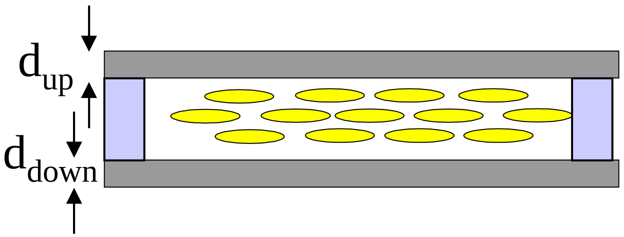
$$T(\omega) = \frac{E_{sample}(\omega)}{E_{reference}(\omega)}$$

Transmission coefficient

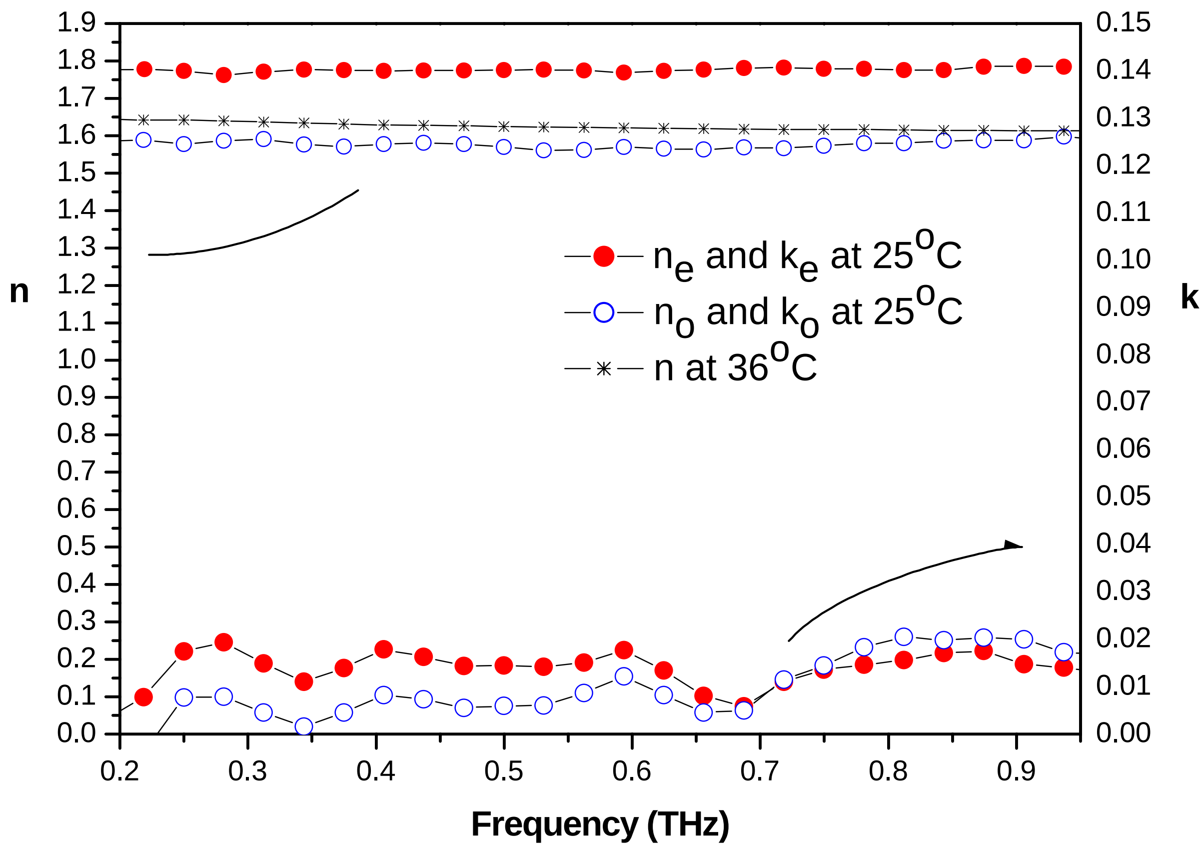
$$= \frac{T_{23'}T_{3'4}}{T_{23}T_{34}}\frac{P_{3'}}{P_3} = \frac{\tilde{n}_{3'}(\tilde{n}_2+1)^2}{(\tilde{n}_2+\tilde{n}_{3'})^2}\times\left[\exp\left(-i\frac{\omega d}{c}(\tilde{n}_{3'}-\tilde{n}_{air})\right)\right]\times FP(\omega)$$

The Complex refractive indices of 5CB

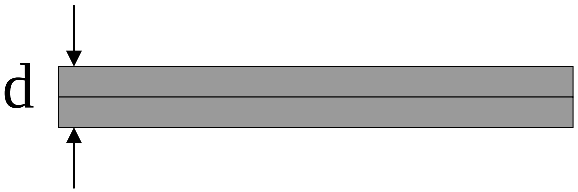
Sample cell:



Filled with 5CB (Merck)
Homogeneous alignment
Cell Gap: 250±2 μm
Substrates: fused silica (3.120 mm)

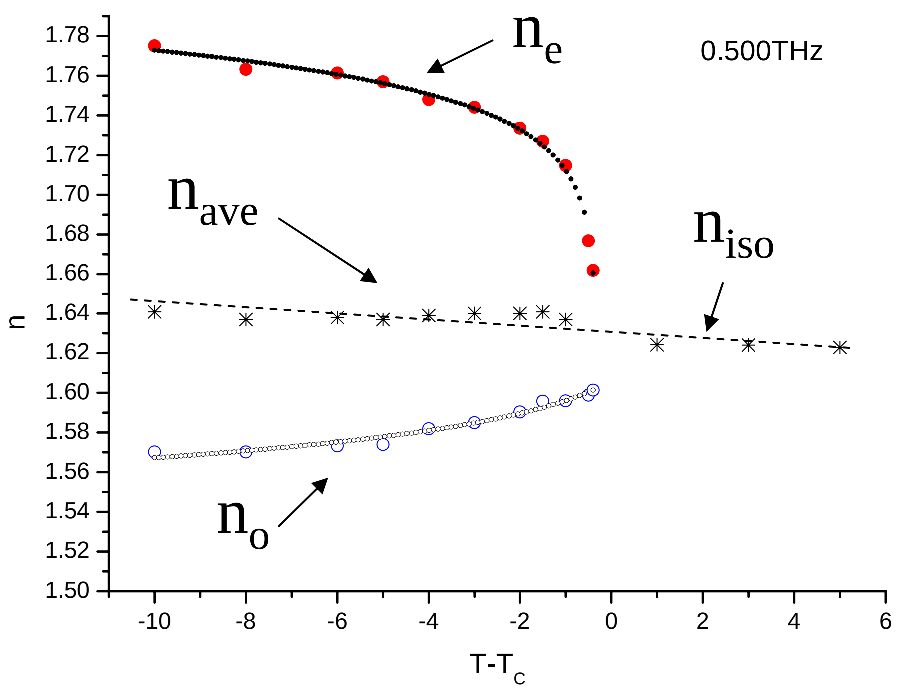


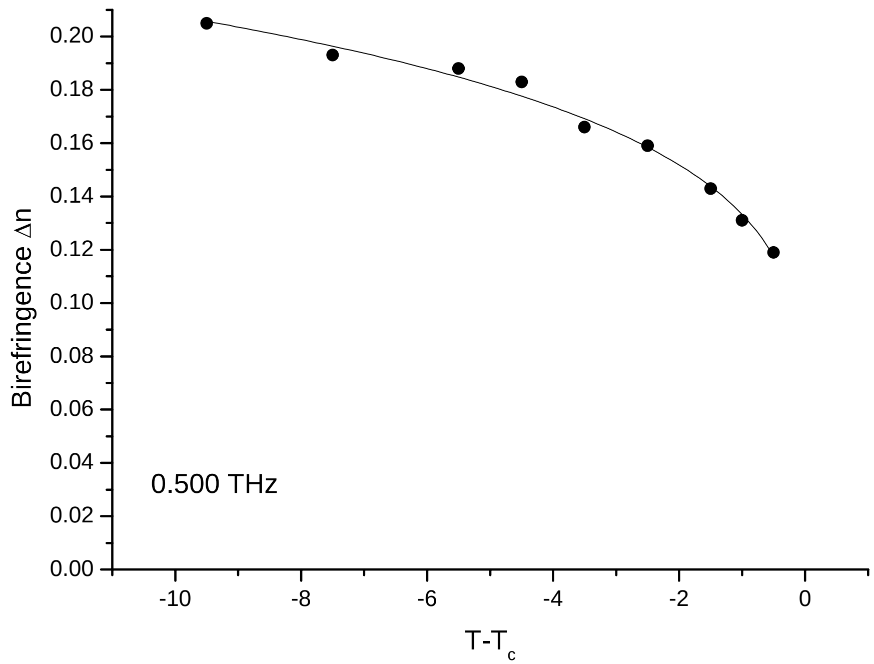
Reference cell:



$$d = d_{up} + d_{down}$$

Temperature Dependence results



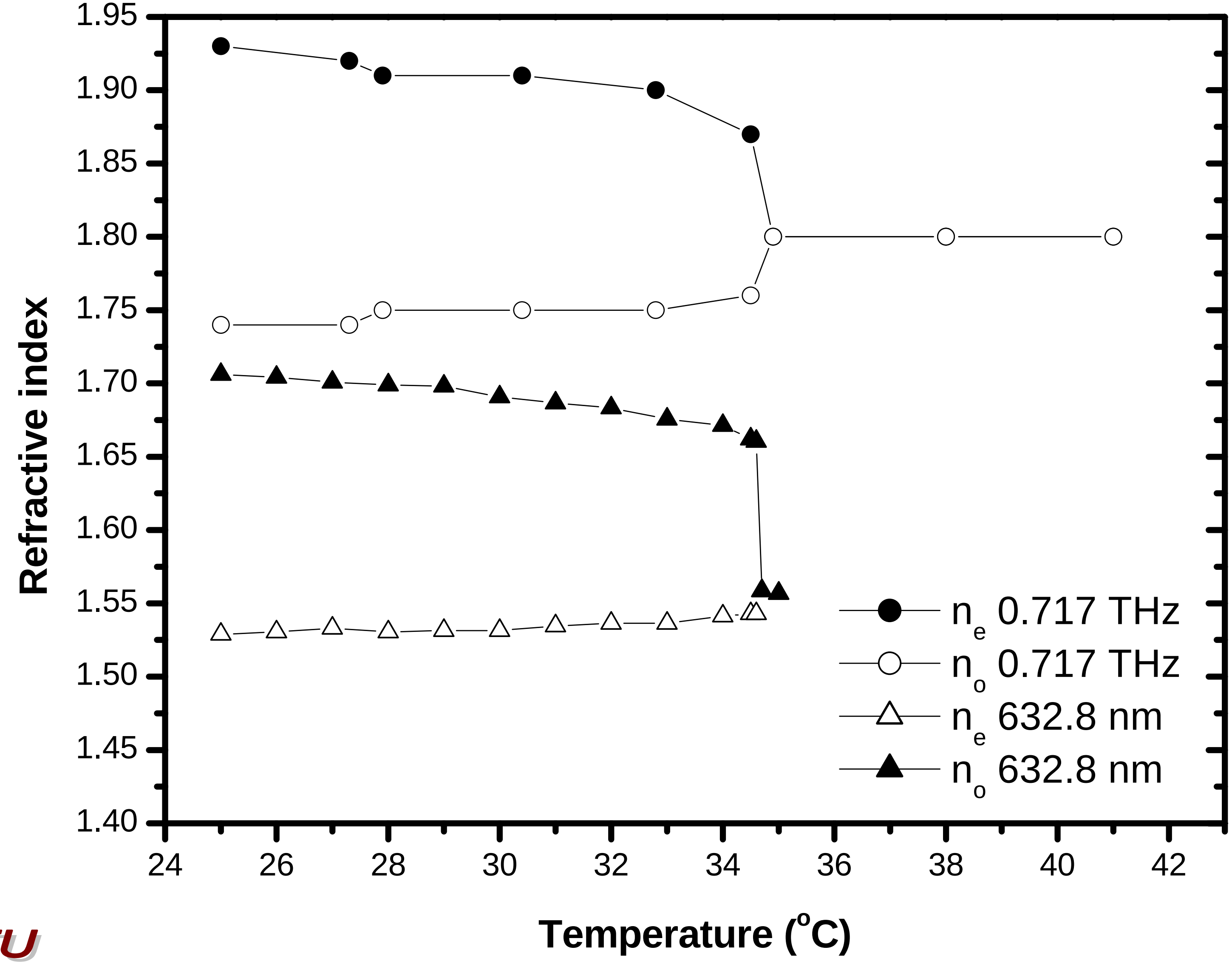


$$n_{ave} = \frac{2n_o + n_e}{3}$$

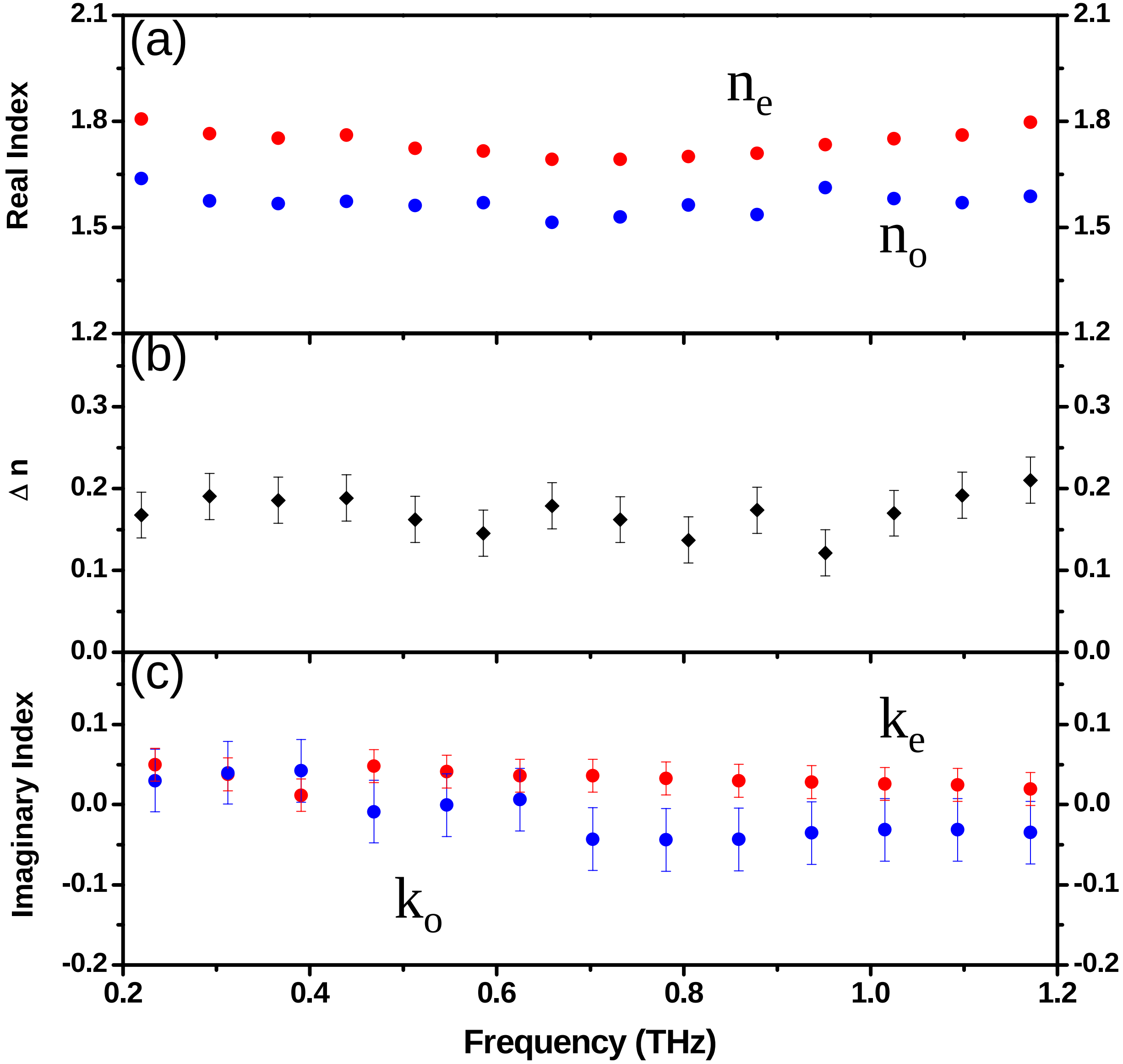
Measured T_c: 34.5℃

Δn of 5CB: 0.15 ~0.2

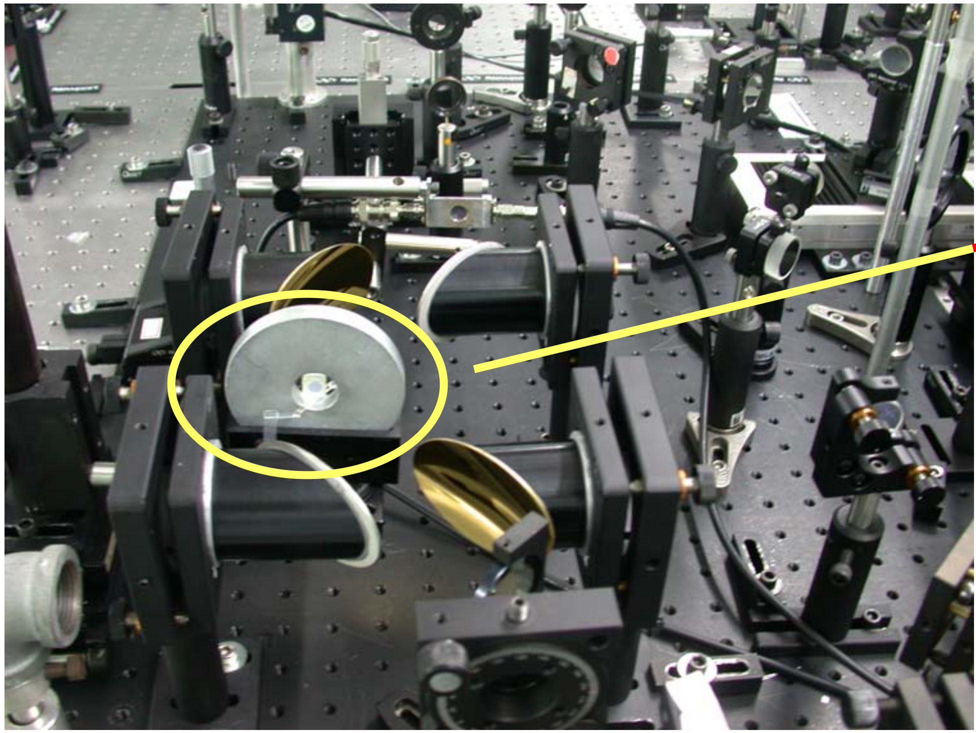
Comparison of THz and visible Data

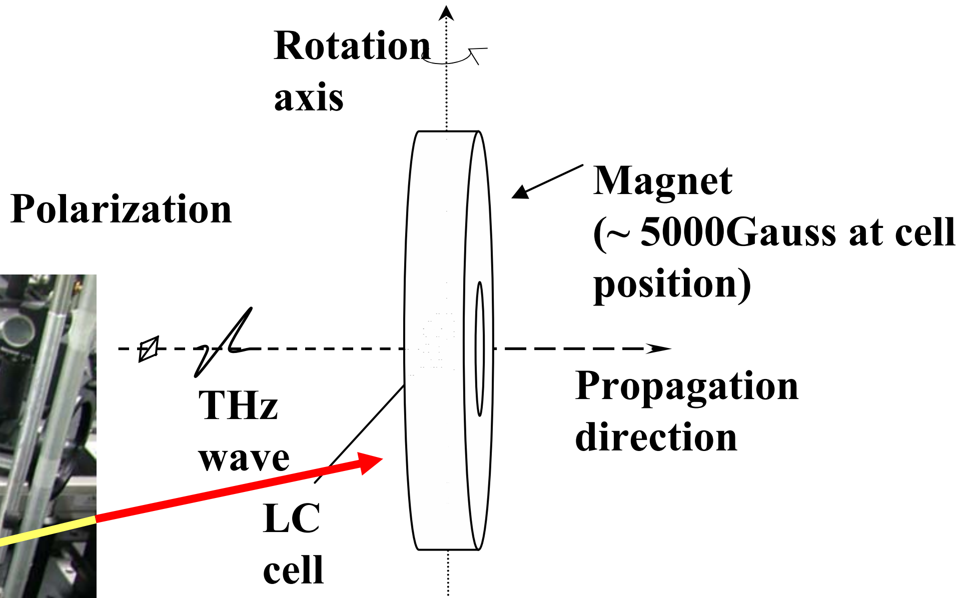


Optical Constant of E7 in the THz range



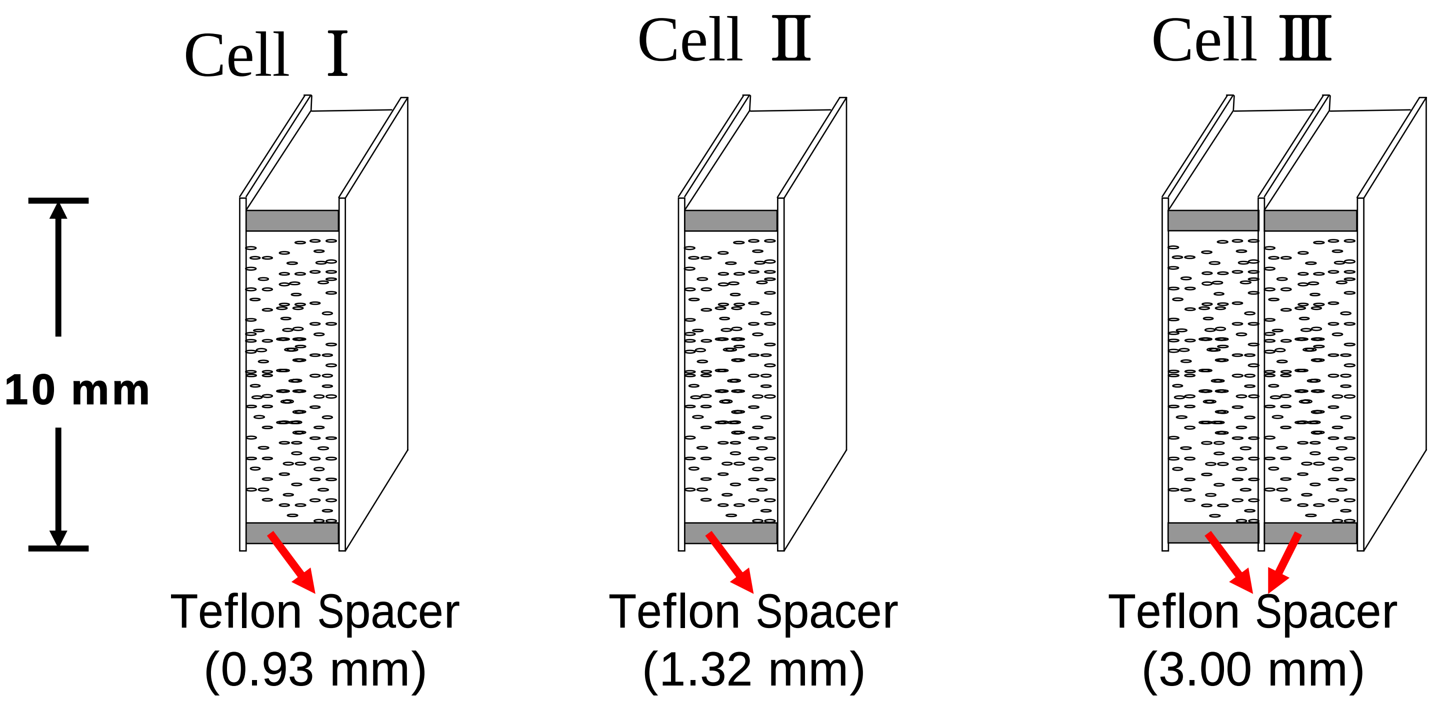
Magnetically controlled LC-based THz phase shifter





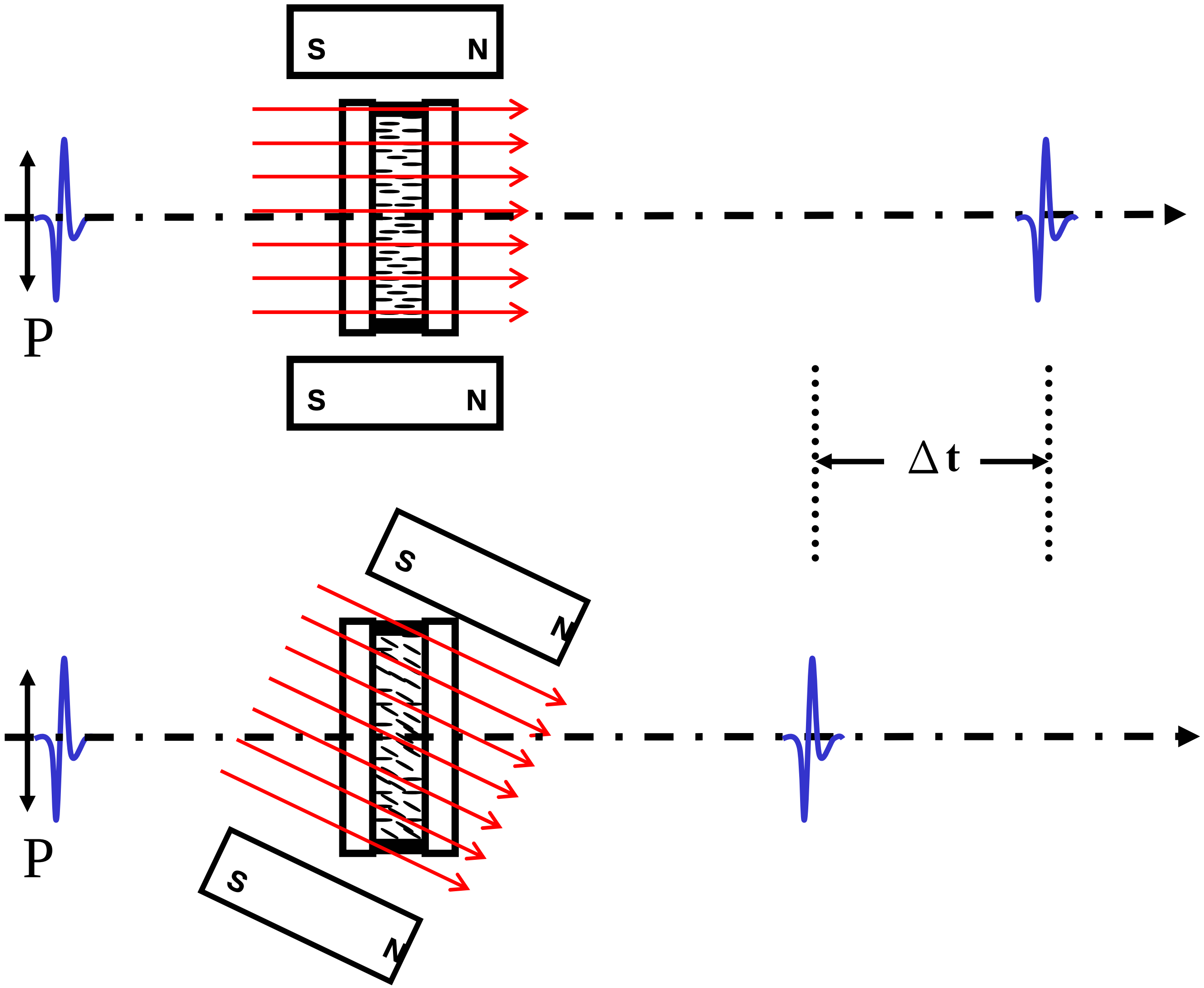
APL, Dec'03, Opt. Exp., June'04, selected by the Virtual Journal on Ultrafast Sciences, Taiwan patent'04, US patents filed

Sandwiched LC Cell Structure



- The fuse silica substrates have been coated DMOAP to obtain the homeotropic alignment.
- The thickness of substrates are about 1.57 mm.

How does the Phase Shifter work?



Theoretical Analysis

Phase shift, $\delta(\theta)$, can be written as

$$\delta(\theta) = \int_0^L \frac{2\pi f}{c} \Delta n_{eff}(\theta, z) dz$$

where L is the thickness of LC layer

Δn_{eff} is the change of effective birefringence

f is the frequency of the THz waves

c is the speed of light in vacuum

- **Threshold magnetic field ≈ 100 Gauss**
- **Magnetic field of magnet ≈ 5000Gauss**

We can assume that the LC molecules are reoriented parallel to the magnetic field direction, the phase shift can then be rewritten as:

$$\delta(\theta) = 2\pi L \frac{f}{c}\left\{\left[\frac{\cos^2(\theta)}{n_o^{\,2}} + \frac{\sin^2(\theta)}{n_e^{\,2}}\right]^{-\frac{1}{2}} - n_o\right\}$$

where L is the thickness of LC layer

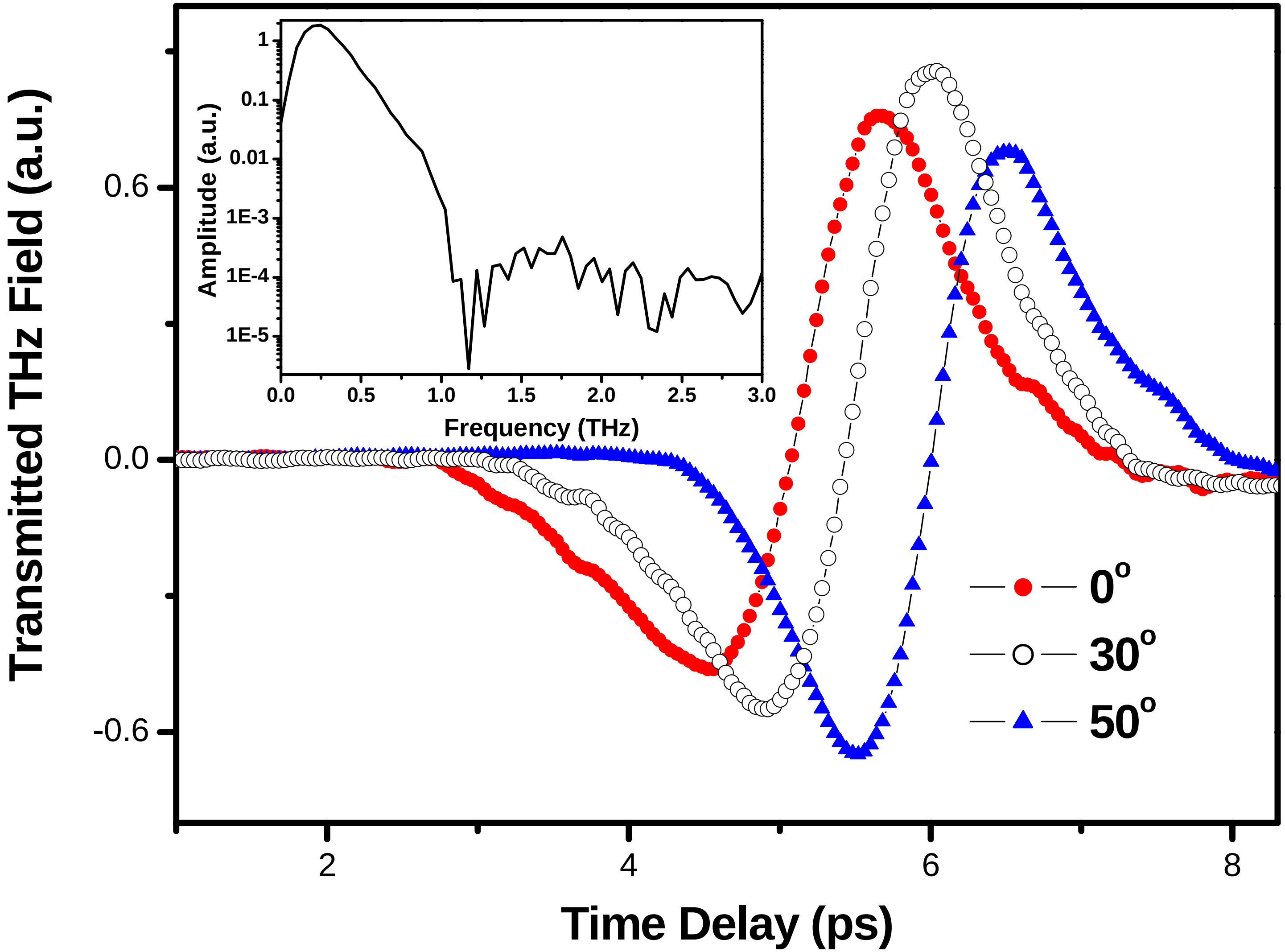
n_o is ordinary refractive index of LC

n_e is the extra-ordinary refractive index of LC

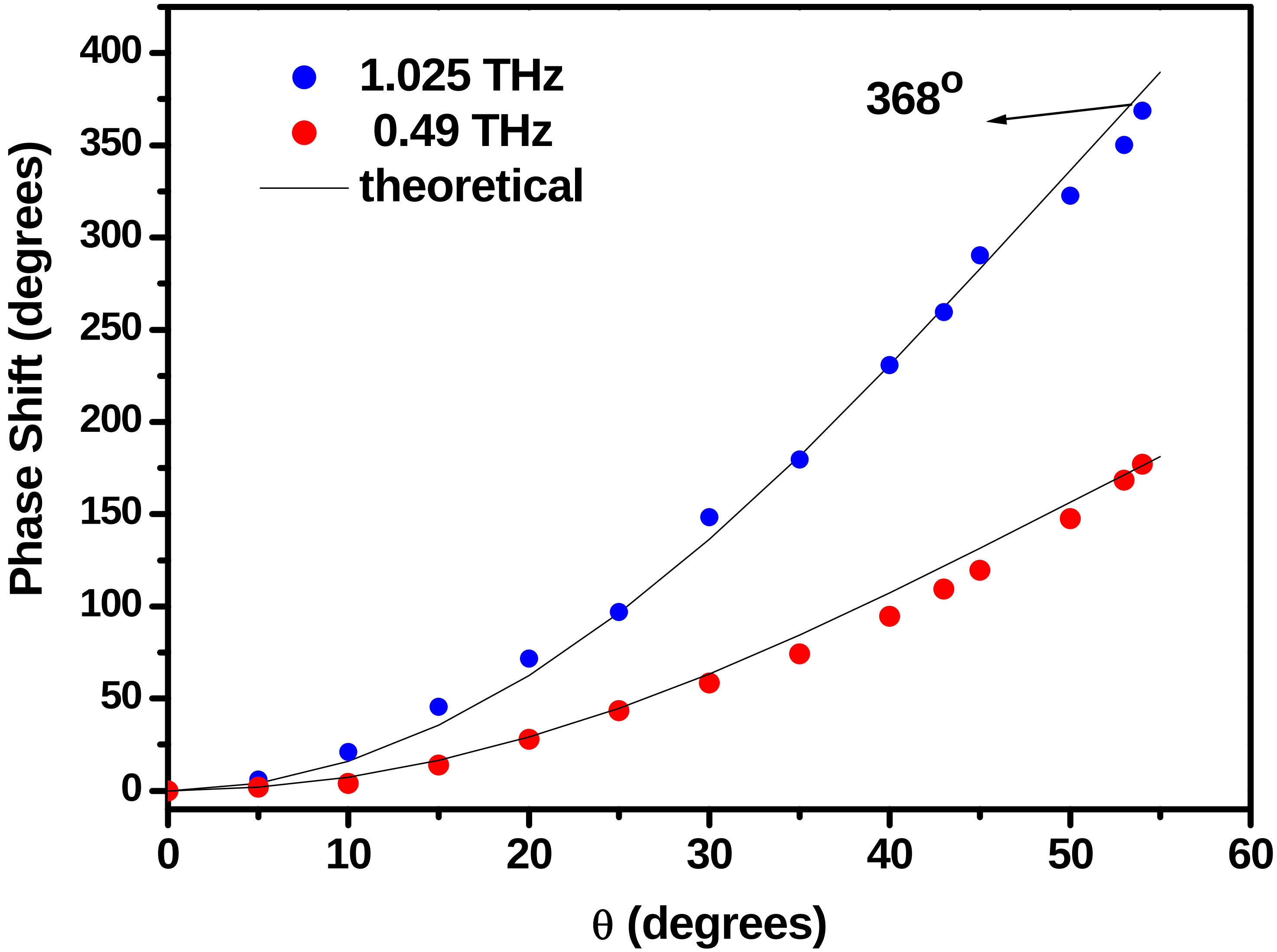
f is the frequency of the THz waves

c is the speed of light in vacuum

Transmitted Waveform through the E7 LC Phase Shifter

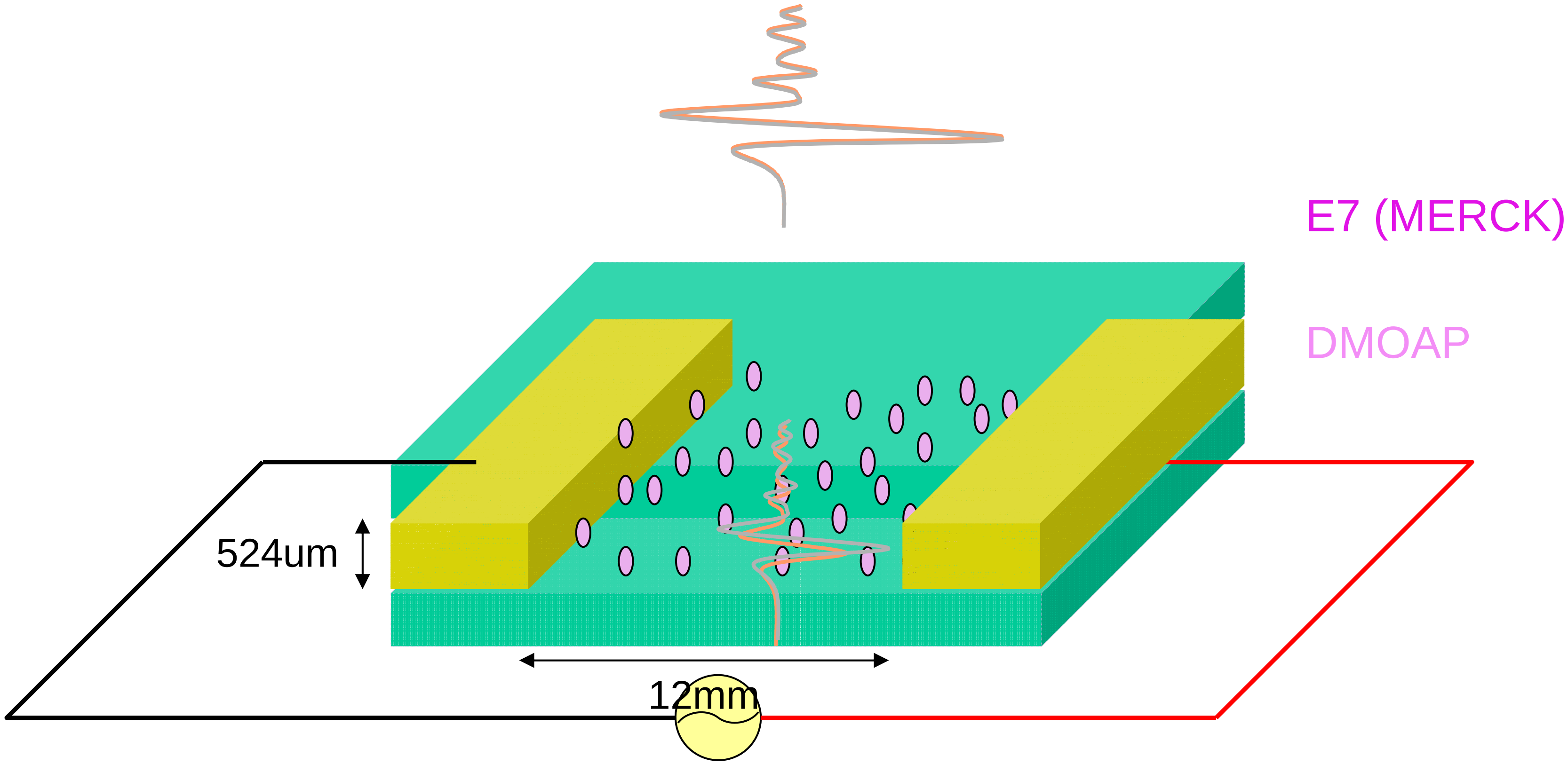


Phase Shift vs Magnetic Field Orientation



NCTU

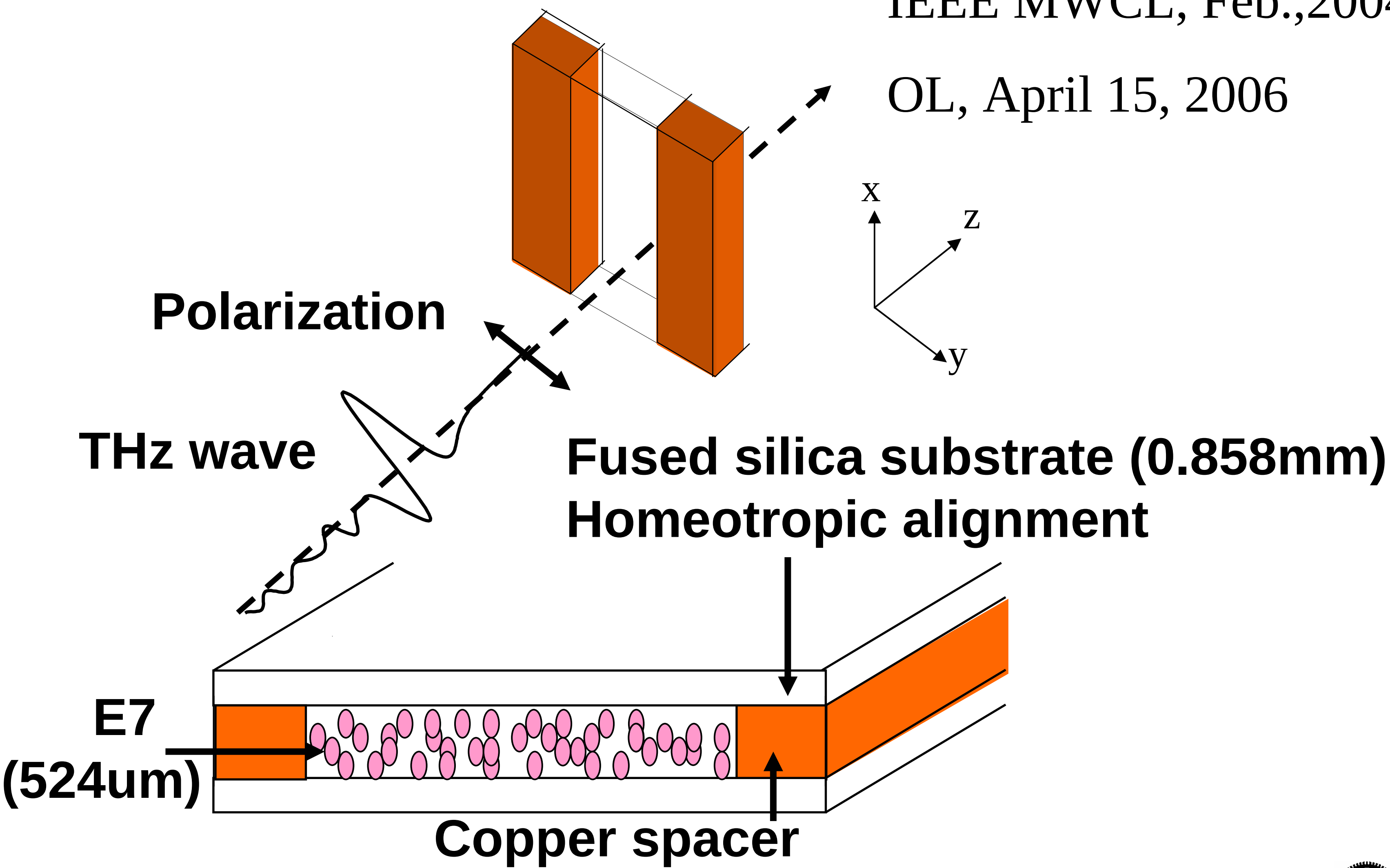
Electrically tunable LC THz phase shifter



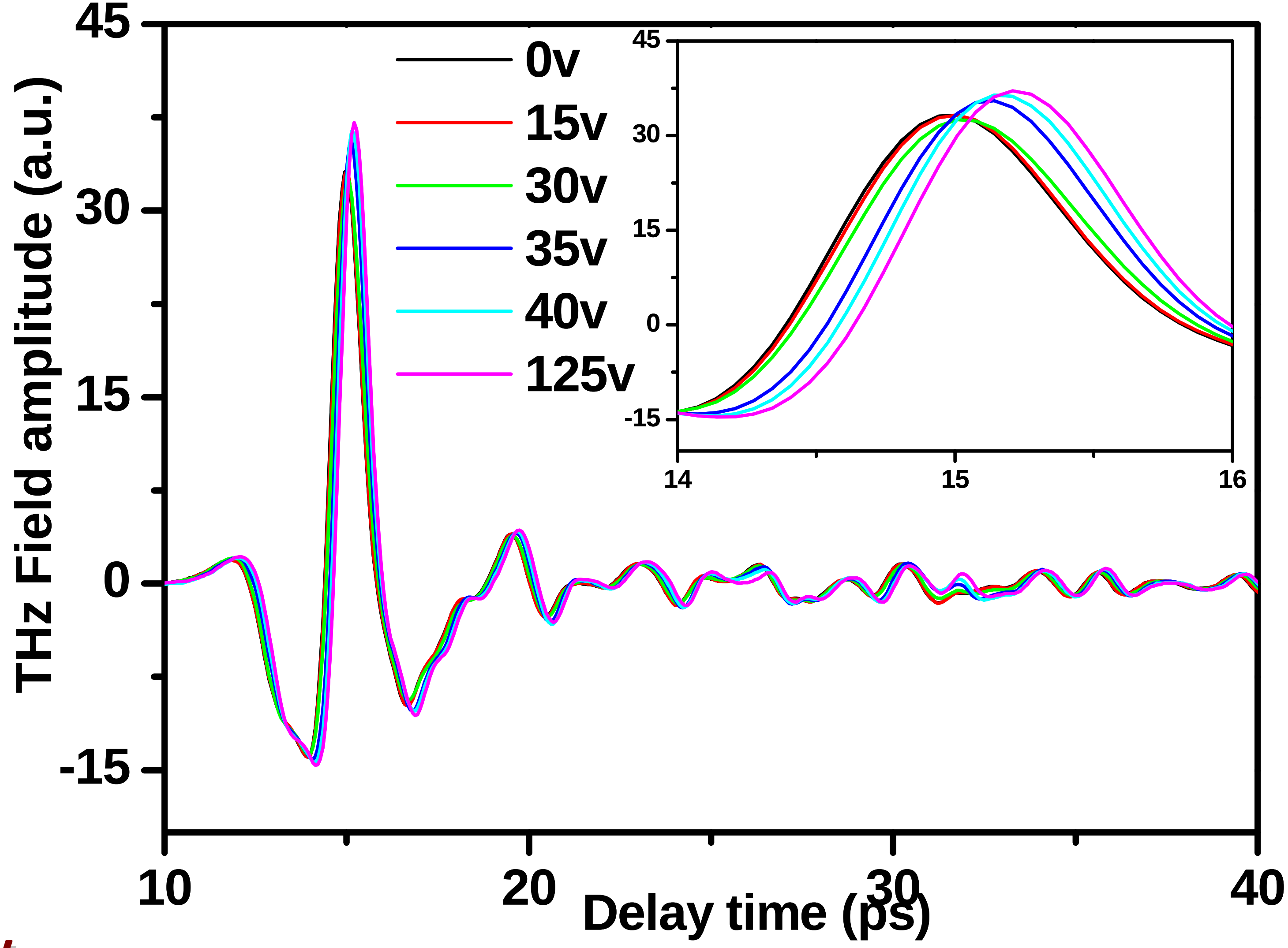
Electrically tunable LC THz phase shifter

IEEE MWCL, Feb.,2004

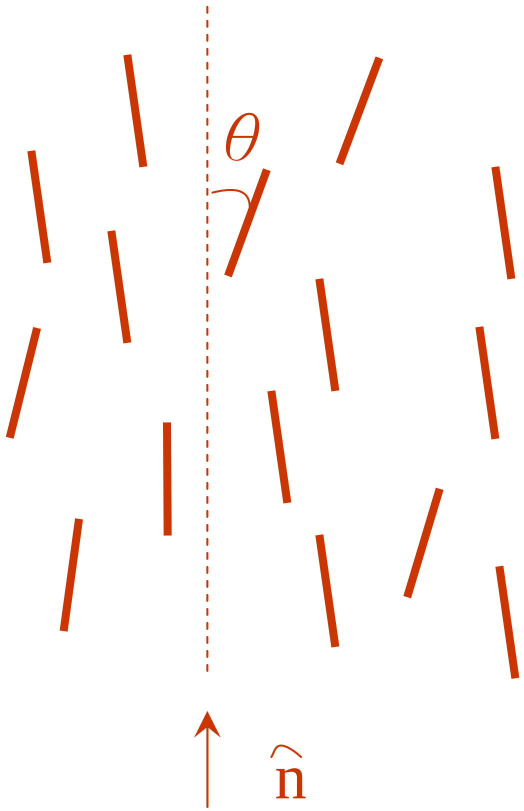
OL, April 15, 2006



Transmitted Waveform through the E7 LC Electrically-tuned Phase Shifter



Theoretical Analysis



$$\frac{z}{d} = \frac{V_{th}}{\pi V}\int_0^{\theta}\left(\frac{1+q\sin^2\theta}{\sin^2\theta_m - \sin^2\theta}\right)^{1/2} d\theta \quad , V > V_{th}$$

$$q = (k_1 - k_3)/k_3$$

$$\Delta n_{eff} = \left[\frac{\cos^2(\theta)}{n_o^{\ 2}} + \frac{\sin^2(\theta)}{n_e^{\ 2}}\right]^{-\frac{1}{2}} - n_o$$

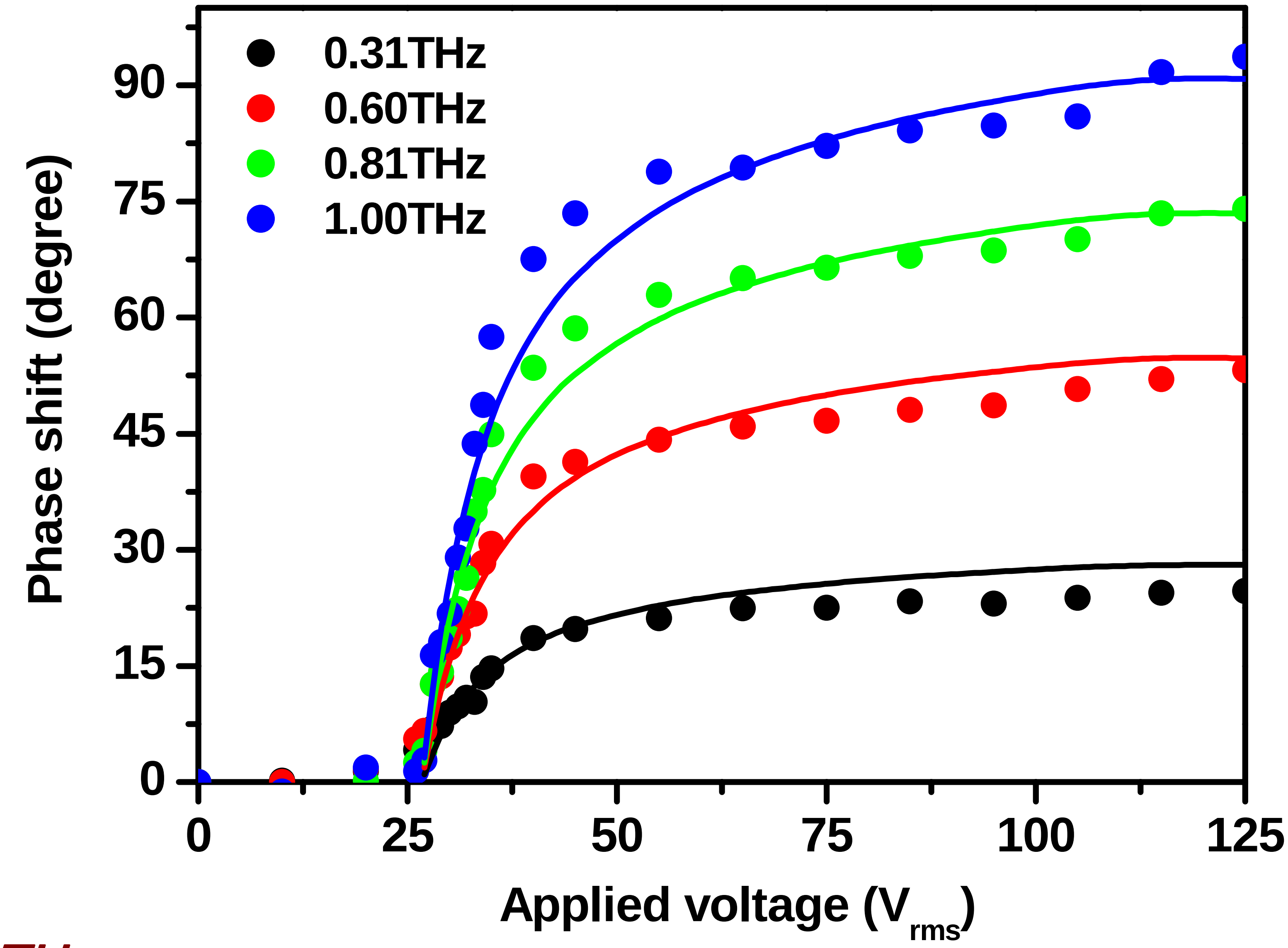
$$\delta(V) = \int_0^d \frac{2\pi f}{c}\Delta n_{eff}(V,z)dz$$

$$V_{th} = \pi\frac{l}{d}\left(\frac{k_3}{\varepsilon_a\varepsilon_o}\right)^{\frac{1}{2}} = 26.9volt$$

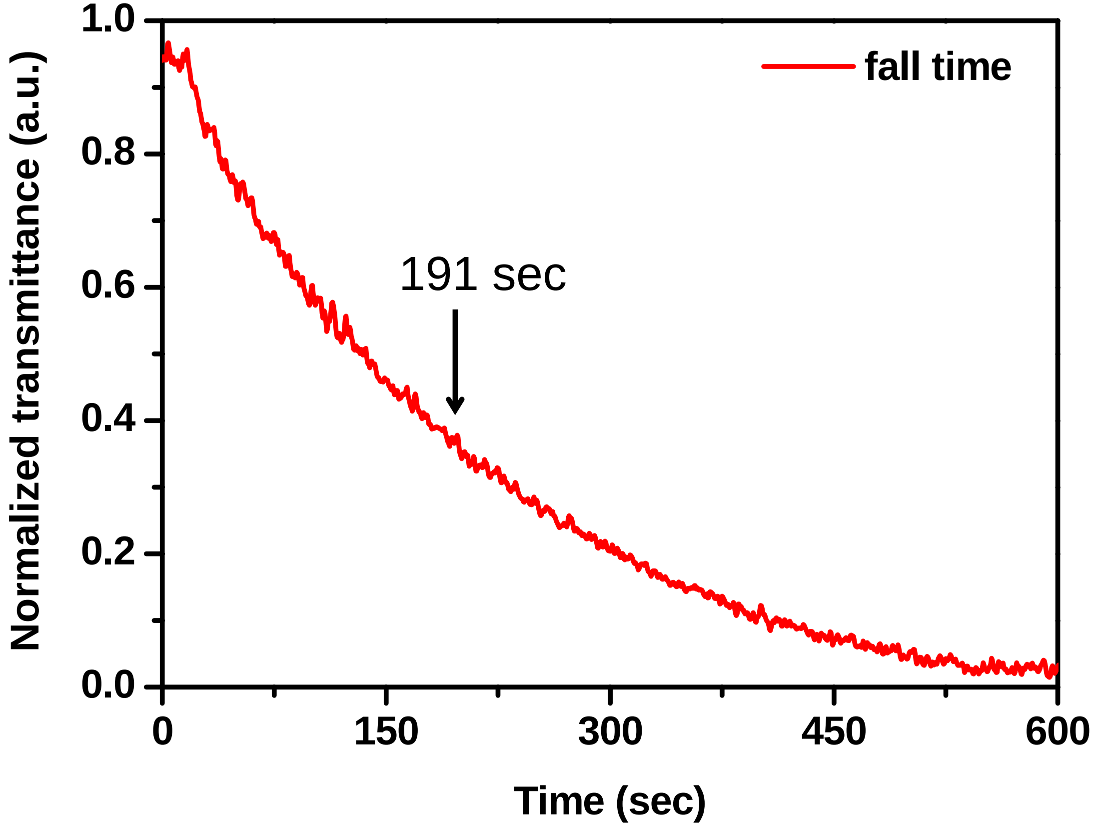
de Gennes, Phys. Liq. Cryst., 1983

Kane, APL **20**(1972)199, **22**, 386 (1973).

Phase Shift vs applied Voltage



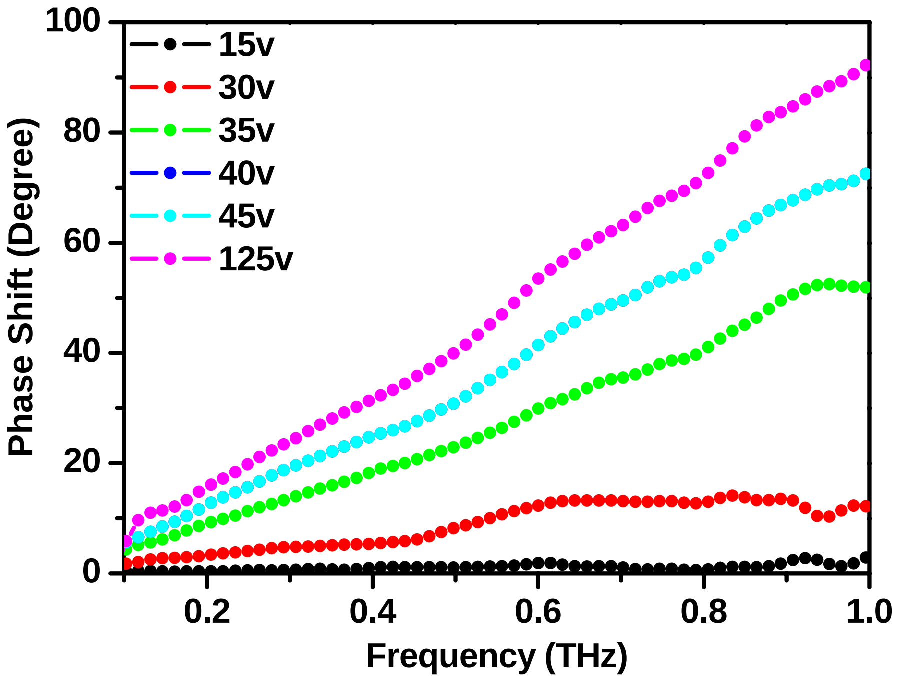
Device Response : Switch-off time



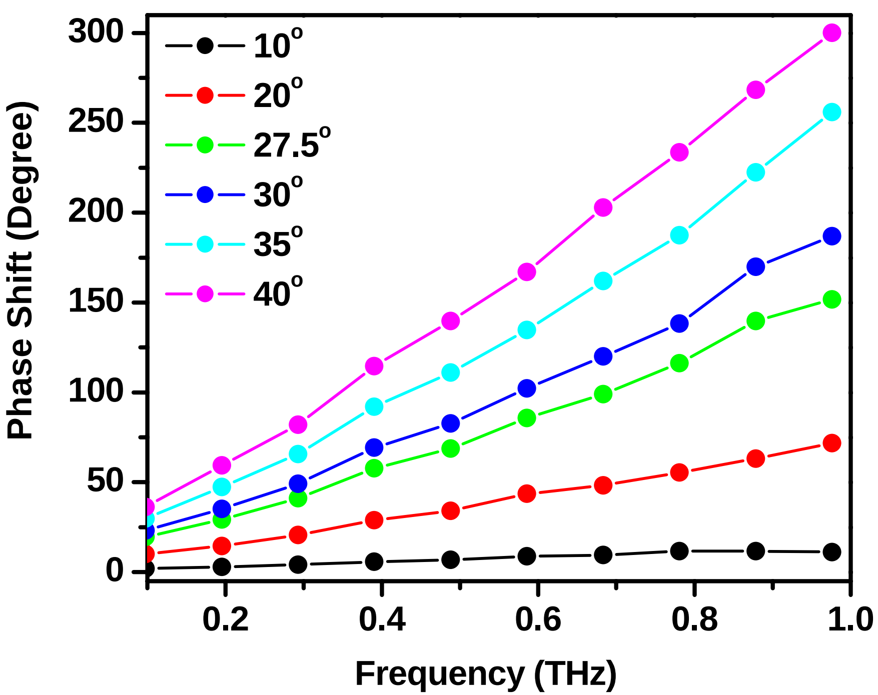
$$I = I_0 e^{-t/\tau_{off}}$$

$$\tau_{\text{off}} = \frac{\gamma}{E_c^2 \varepsilon_0 \varepsilon_a} = 165\,\text{ms}$$

Phase Shift: E vs B tuned

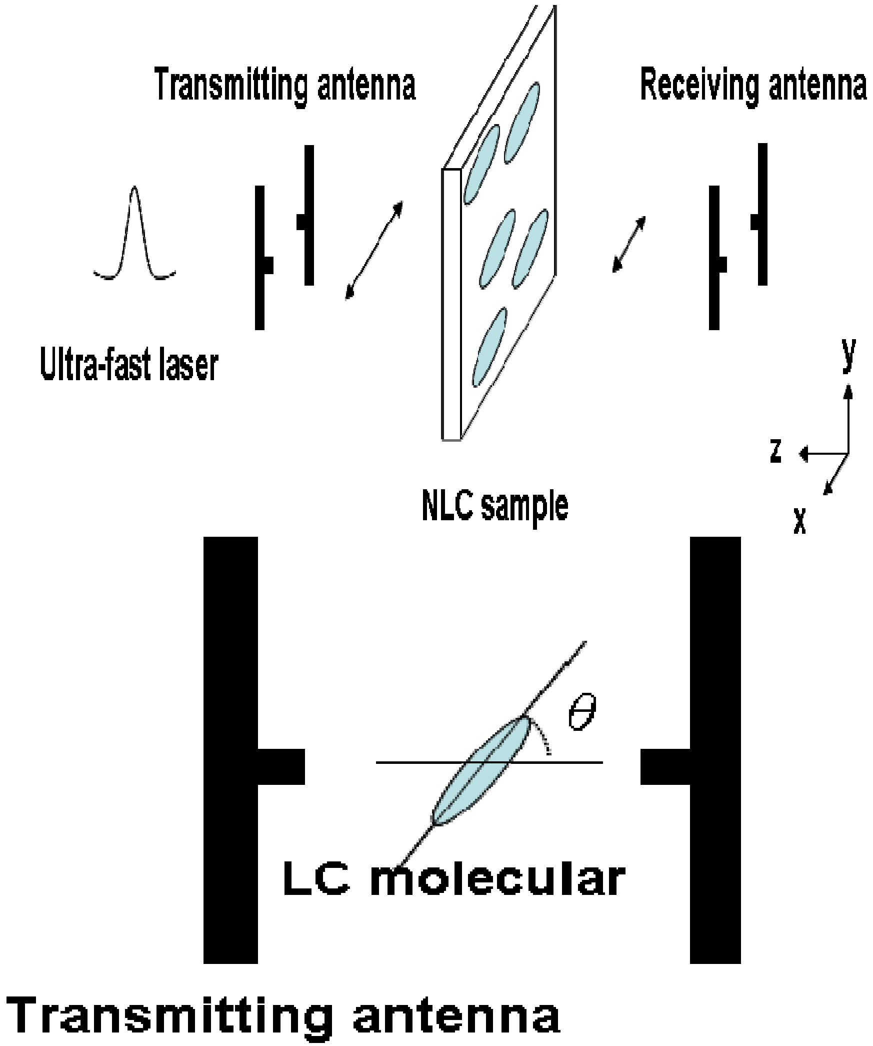


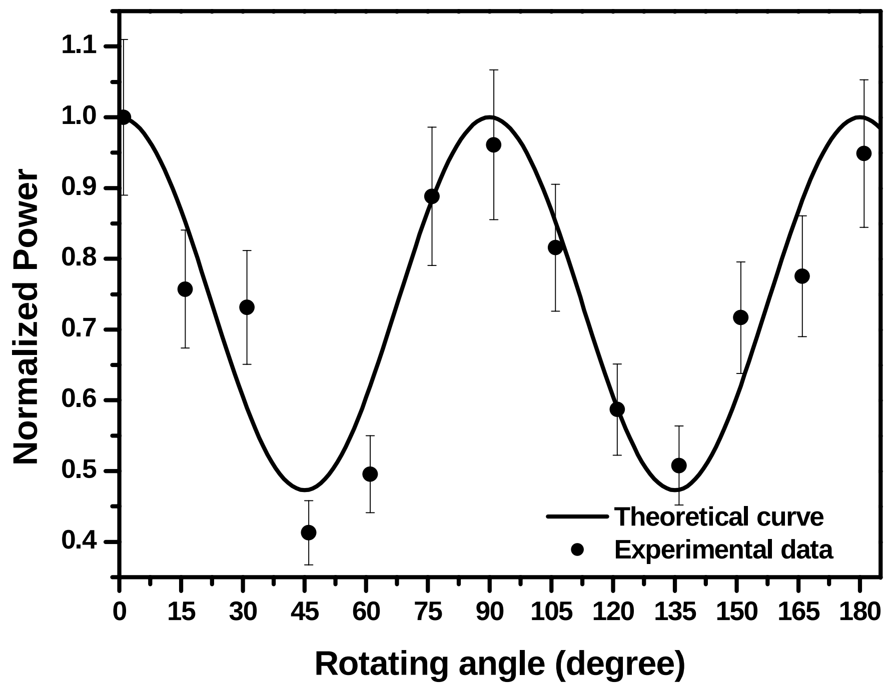
E-field tuned LC THz Phase Shifter



B-field tuned LC THz Phase Shifter

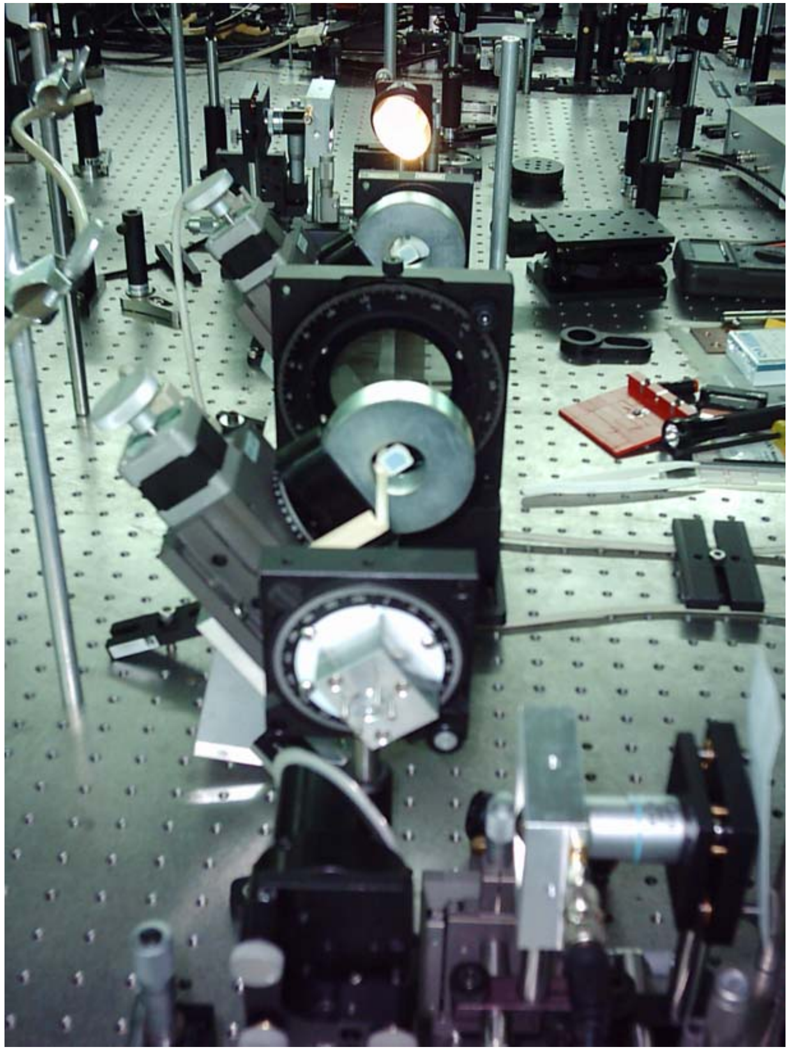
Quarter wave plate/Compensator

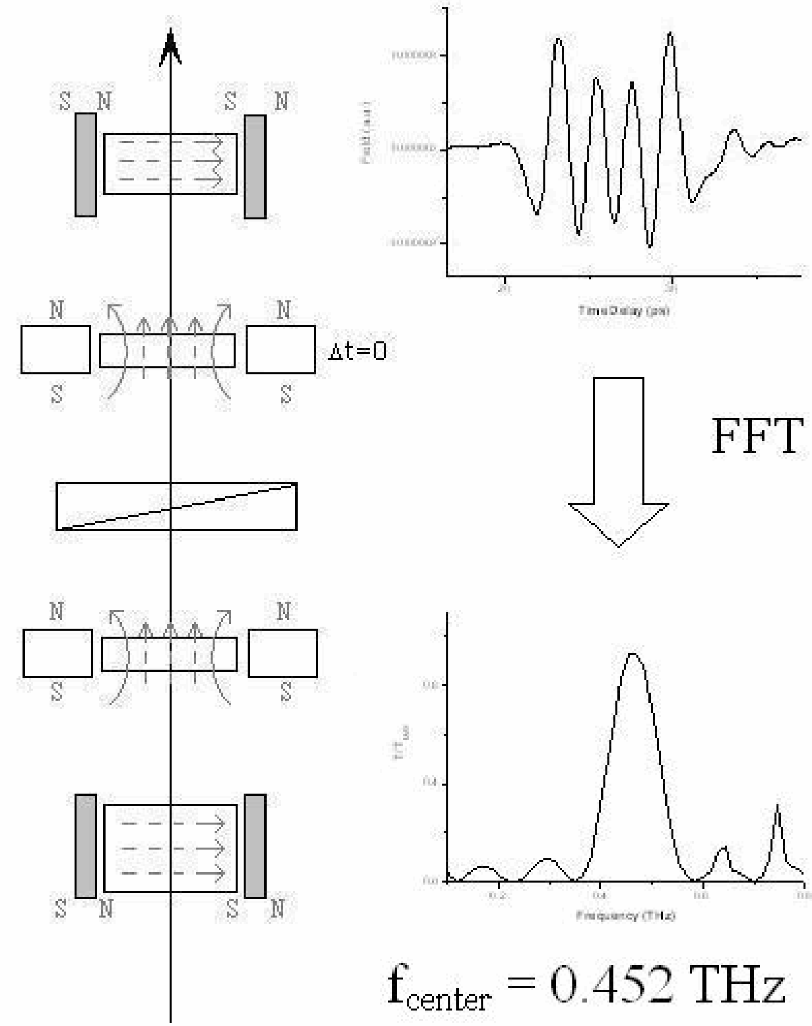




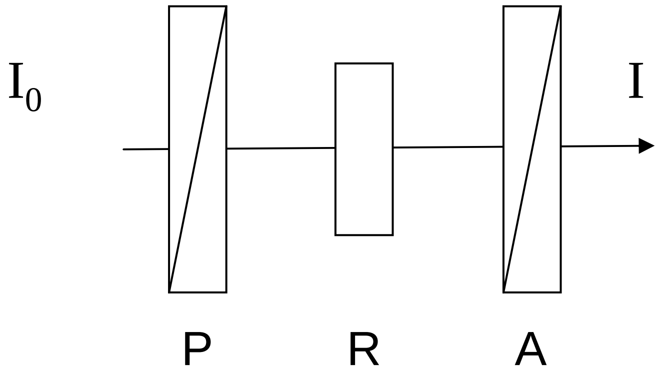
rotated axis is the propagation of THz beam

Lyot-type LC Tunable THz Filter





Principle of the Lyot Filter



Polarizer $\parallel$ Analyzer

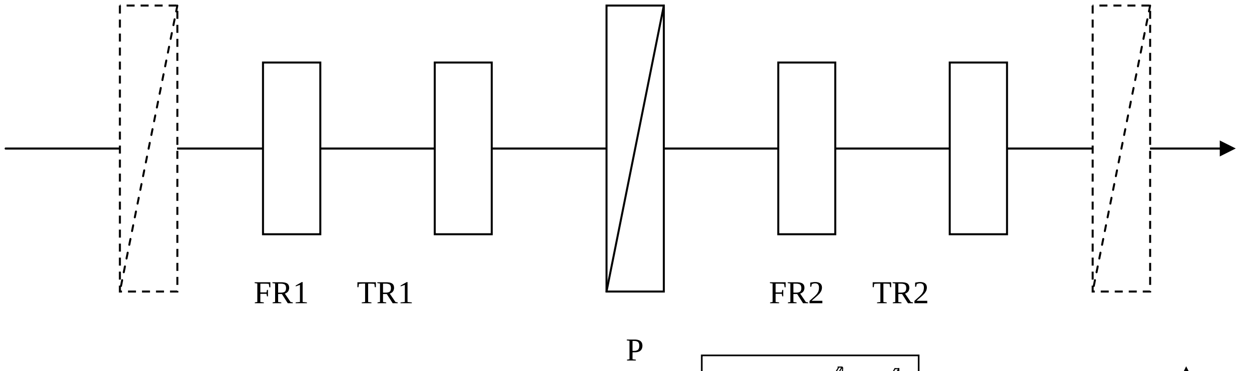
R: Retarder with retardation of Γ

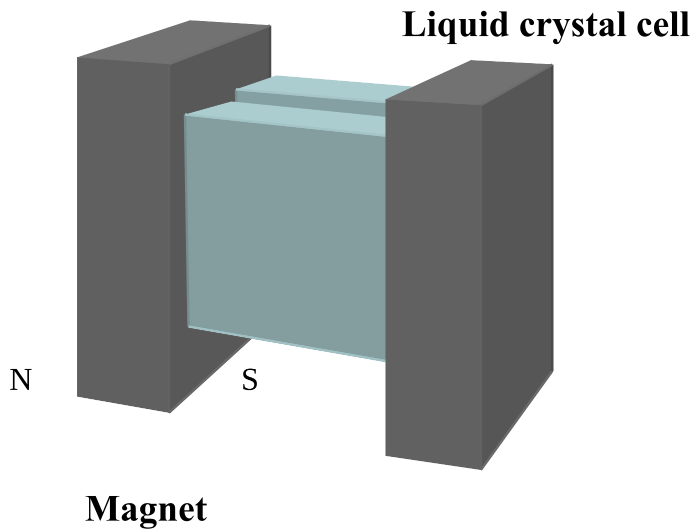
$$T \equiv \frac{I}{I_0} = \cos(\frac{\Gamma}{2})^2 = \cos(\pi \cdot f \cdot \Delta\tau)^2$$

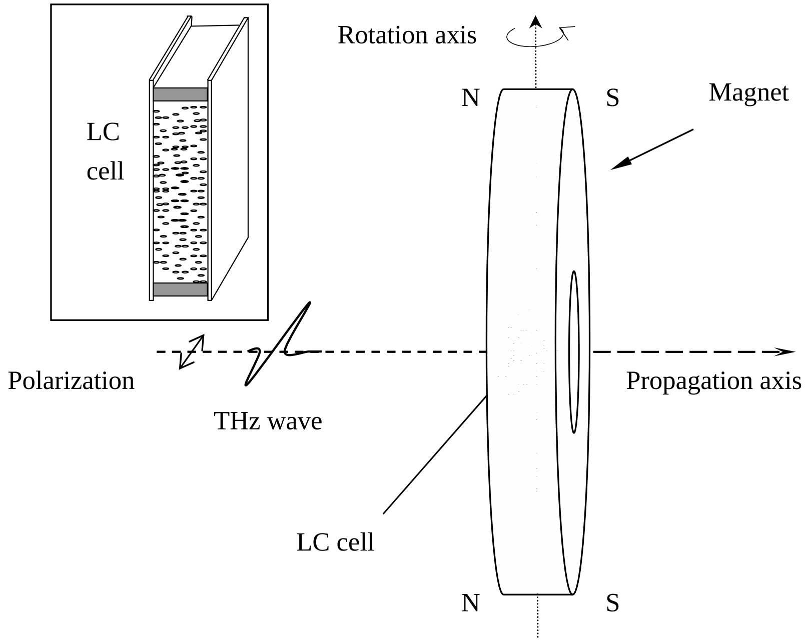
$$(\Gamma = \frac{2\pi \cdot \Delta n \cdot d}{\lambda} = \frac{2\pi \cdot \Delta n \cdot d \cdot f}{c} = 2\pi \cdot \Delta\tau \cdot f)$$

T is function of frequency (f) → ***Filter***

Sketch of LC THz wavelength selector

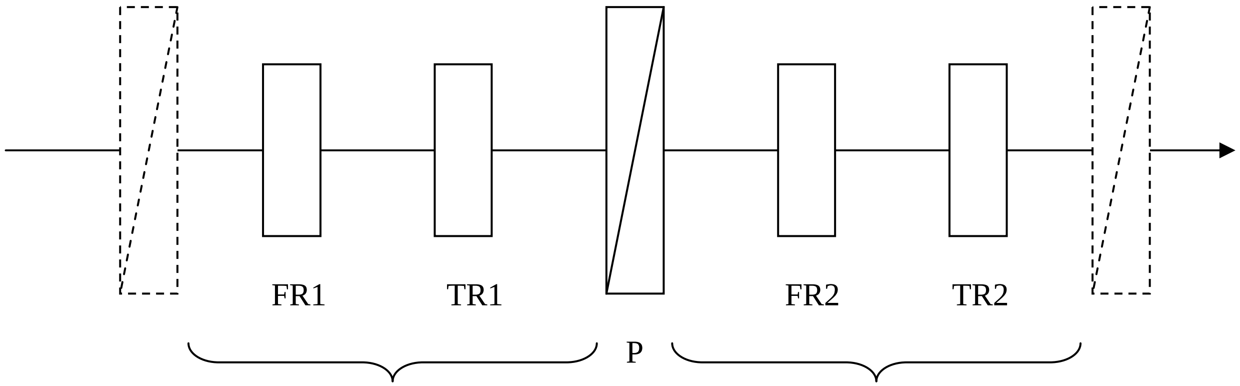




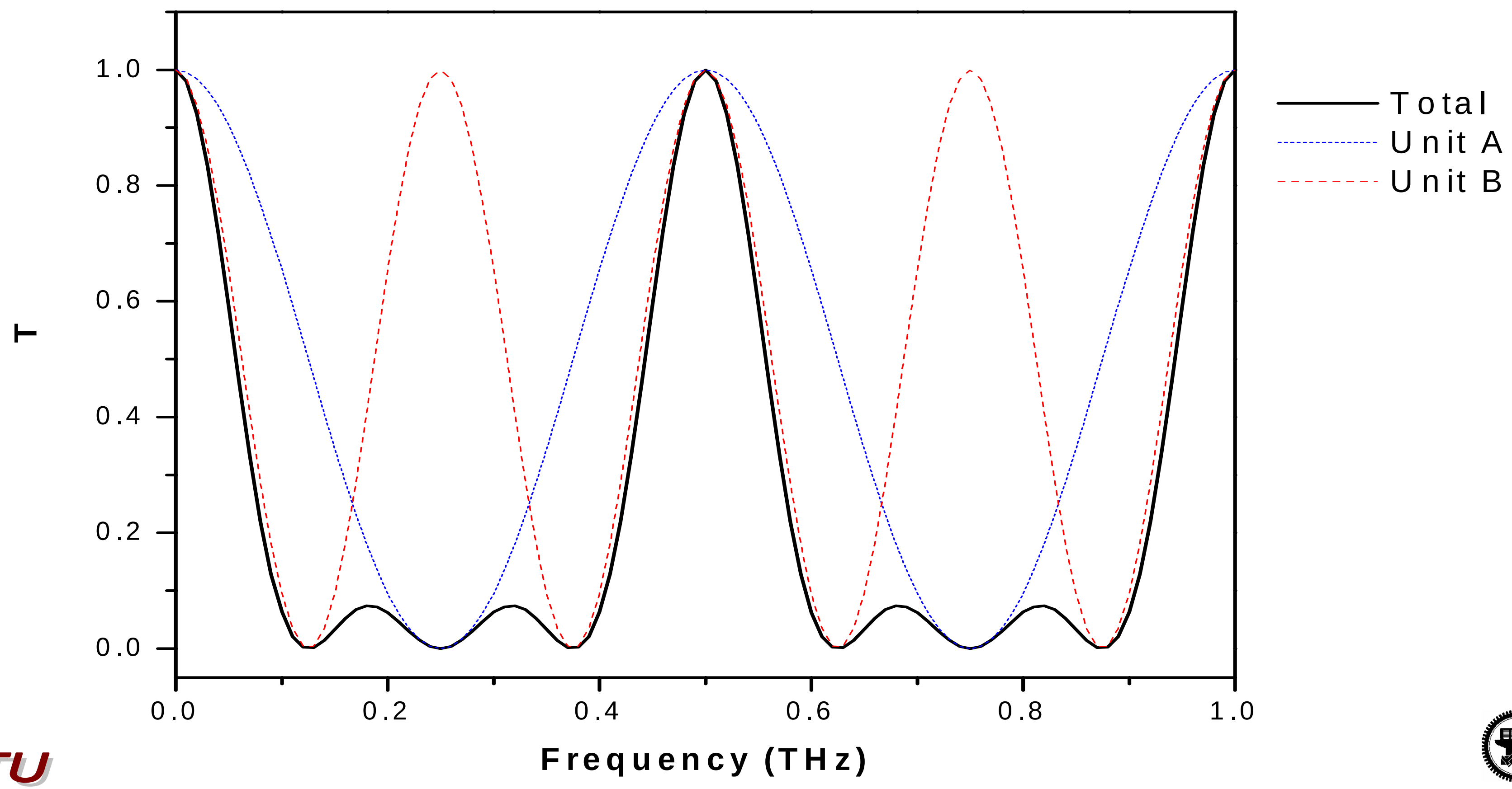


FR1 and FR2 are fixed retarder with 4.5-mm and 9-mm homogeneous LC cells

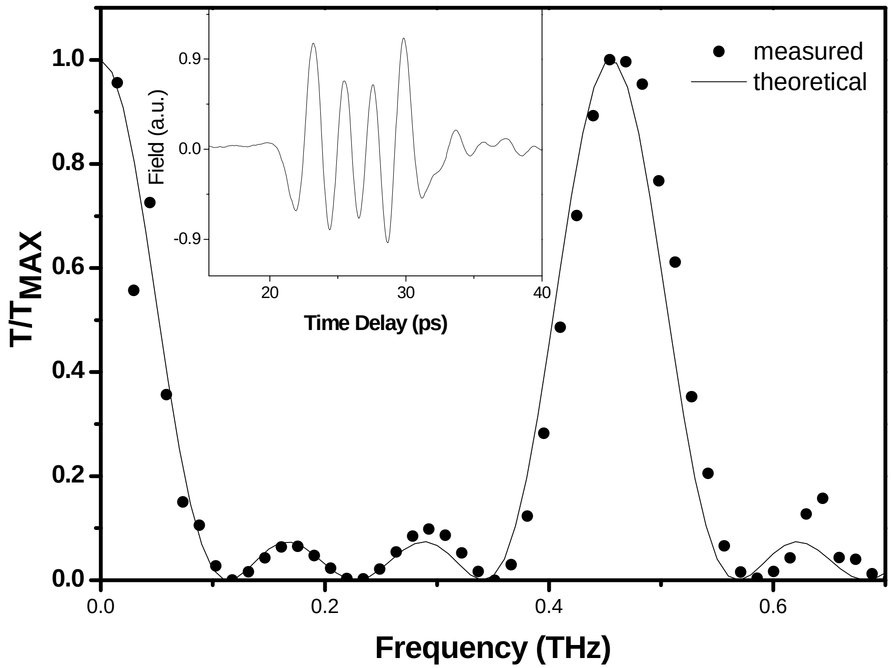
TR1 and TR2 are tunable retarder with 2-mm and 4-mm homeotropic LC cell

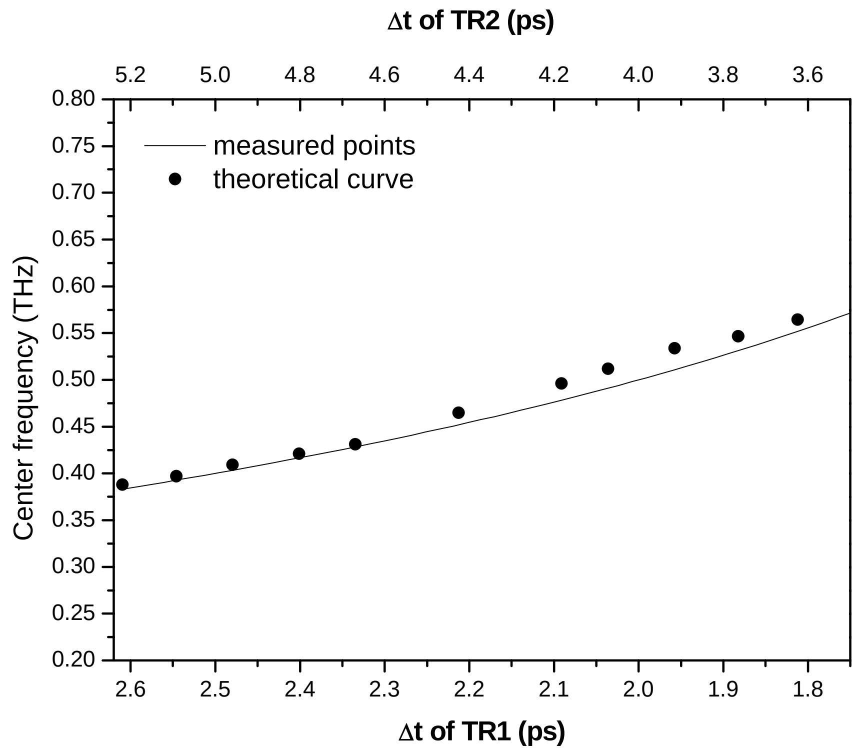


Unit A : Unit B = 1 : 2 (retardation)



Lyot-type LC THz filter: Results

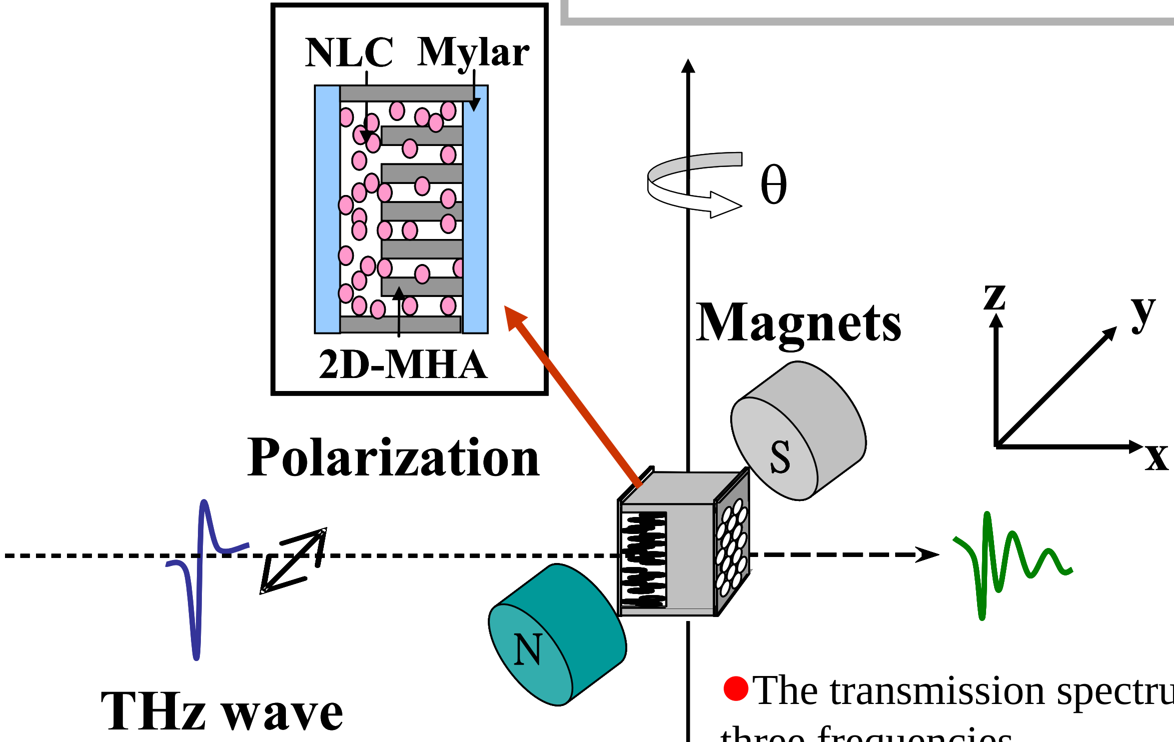




Tunable range : 0.388 ~ 0.564 THz (~ 40 % of f_{center}) !

Tunable THz Photonic Crystal Filter Using Nematic Liquid Crystal

- The 2D-MPC sample was made from 0.5 mm-thick Al plate
- The triangular lattice constant: s = 0.99 mm,
- The diameter of each hole: d = 0.56 mm.



$$\nu_{\text{cutoff}} = 1.841 \frac{c}{\pi d}$$

$$\nu_{diff} = 2c' / \sqrt{3}s$$

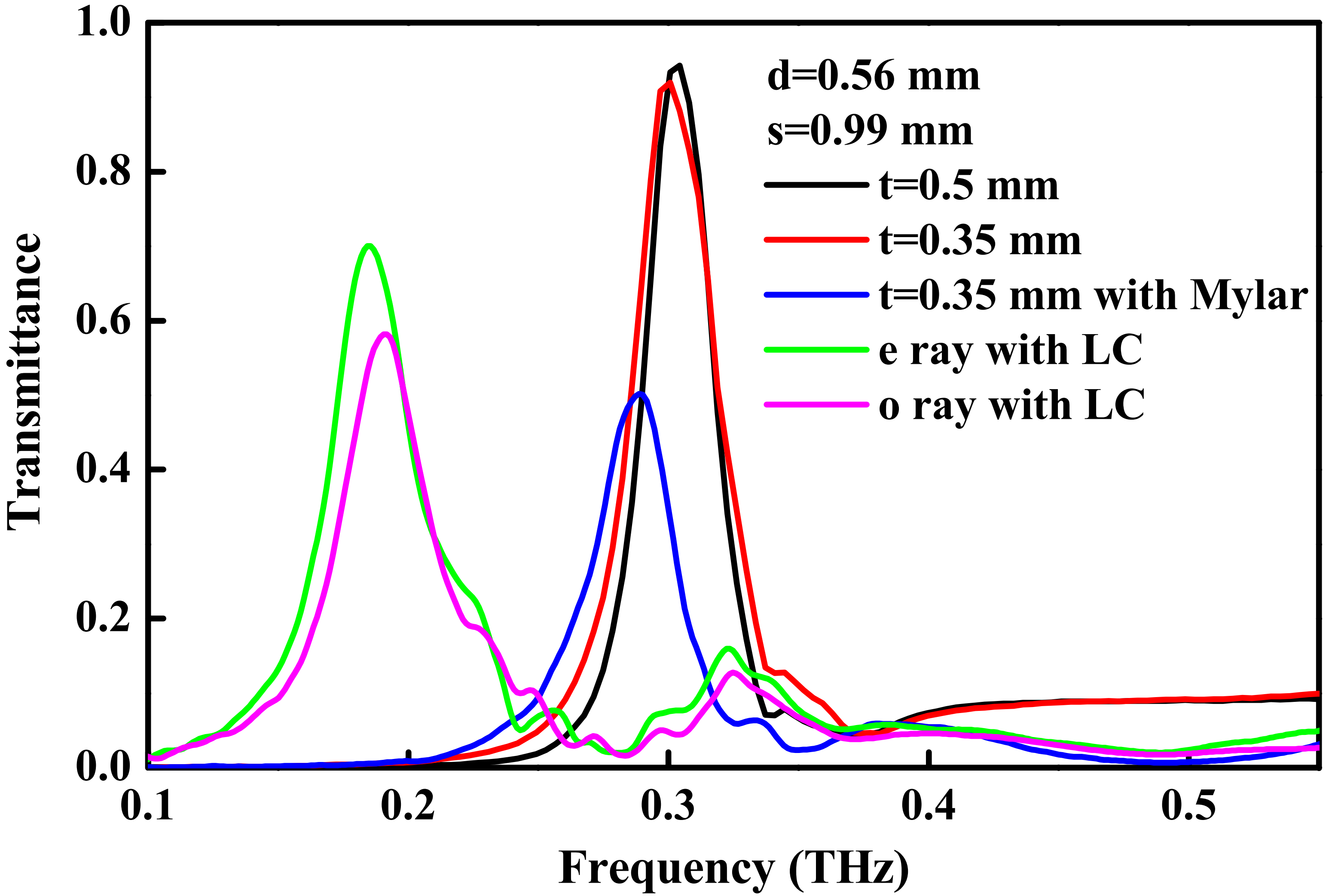
$$\nu_{spp} = \left| \vec{k}_{in} + \vec{G} \right| \frac{c_0}{2\pi} \sqrt{\frac{\varepsilon_m + \varepsilon_d}{\varepsilon_m \varepsilon_d}} \approx \frac{\nu_{diff}}{n_d}$$

$$\nu_R = \nu_{spp} \cong \frac{\nu_{diff}}{n_d}$$

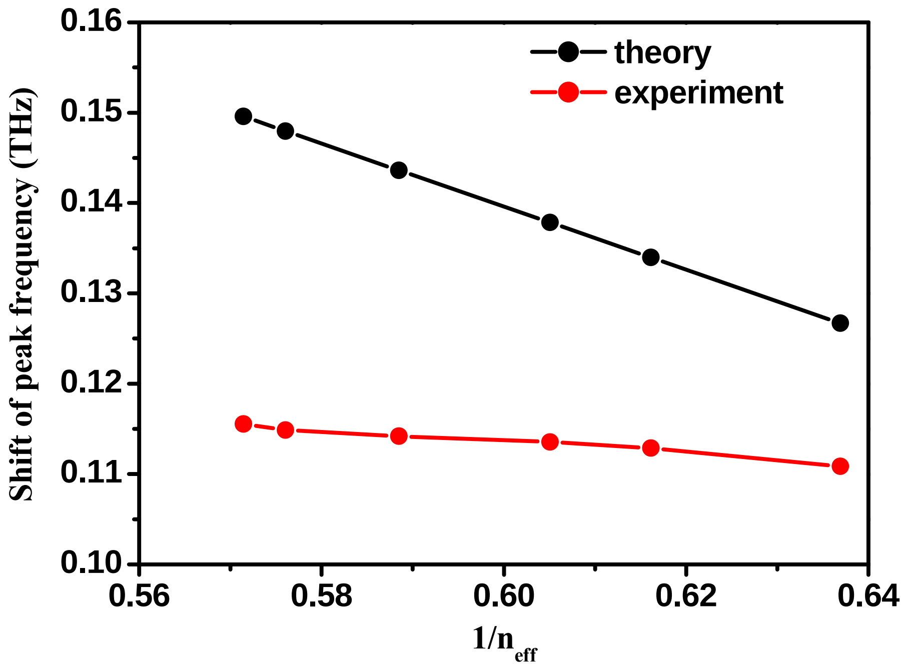
- The transmission spectrum of the 2D-MHA is characterized by three frequencies.
- The band-pass peak frequency is above the cutoff frequency.
- The transmittance is several times larger than the porosity of the holes.

NCTU

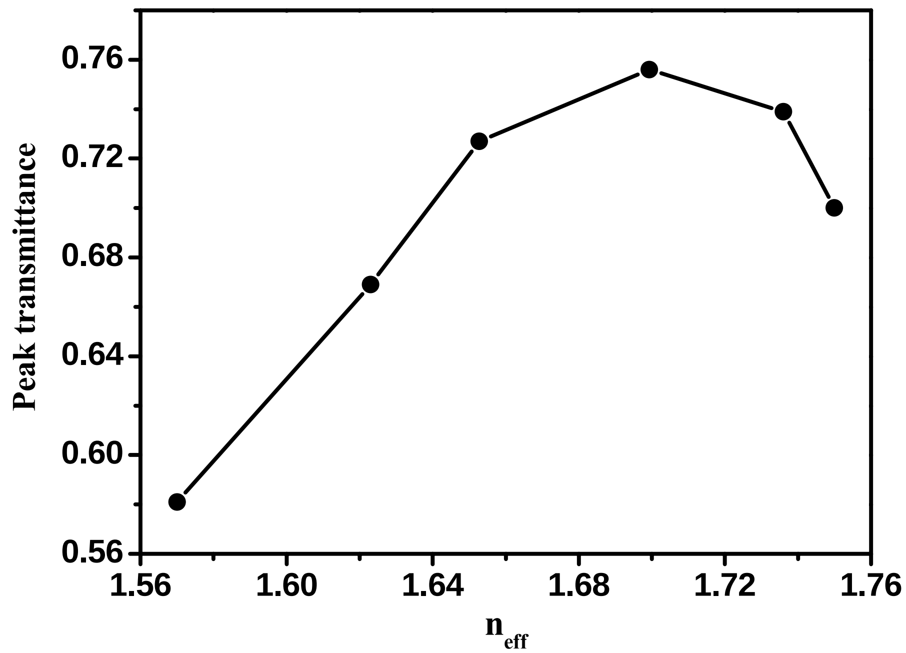
Transmission of the 2D-MPC w/w.o. LC



Frequency shifter and Peak Transmittance of the LC Tunable THz Photonic Crystal



Frequency Shift



Peak Transmittance

Summary

- Optical constants of several LCs measured in the THz range. Birefringence of 5CB and E7 comparable to those in the visible. Attenuation negligible.
- Several LC-based THz devices demonstrated.

1. Room-temperature 2π magnetically tunable THz phase shifter
2. LC-based THz quarter-wave plate w/fine electrical tuning.
3. LC-type tunable Lyot-type THz filter.
4. LC-type tunable photonic crystal THz filter.

References (LC THz Optics)

1. Tsong-Ru Tsai, Chao-Yuan Chen, Ci-Ling Pan, Ru-Pin Pan, and X.-C. Zhang, "THz Time-Domain Spectroscopy Studies of the Optical Constants of the Nematic Liquid Crystal 5CB", Appl. Optics, Vol. 42, No. 13, pp 2372-2376 (May 1, 2003) .
2. Ru-Pin Pan, Tsong-Ru Tsai, Chao-Yuan Chen, and Ci-Ling Pan, "Optical Constants of Two Typical Liquid Crystals 5CB and PCH5 in the THz Frequency Range", J. of Biological Physics, V. 29, No.2-3, pp.335-338, July, 2003.
3. Ru-Pin Pan, Tsong-Ru Tsai, Chiunghan Wang, Chao-Yuan Chen, And Ci-Ling Pan, "The Refractive Indices of Nematic Liquid Crystal 4, 4'-n-pentylcyanobiphenyl in the THz Frequency Range," Mol. Cryst. Liq. Crystl., Vol. 409, pp. 137-144, 2004.
4. Tsong-Ru Tsai, Chao-Yuan Chen, Ci-Ling Pan, Ru-Pin Pan, and X.-C. Zhang, "Room Temperature Electrically Controlled Terahertz Phase Shifter," IEEE Microwave and Wireless Components Lett., Vol. 14, No. 2, pp. 77-79, February 2004.
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